НАЦІОНАЛЬНА АКАДЕМІЯ АГРАРНИХ НАУК УКРАЇНИ

ІНСТИТУТ ВОДНИХ ПРОБЛЕМ І МЕЛІОРАЦІЇ

ISSN 2616-5562 (Online)
ISSN 2616-5643 (Print)

МЕЛІОРАЦІЯ
І ВОДНЕ ГОСПОДАРСТВО

№ 1 · 2025

Міжнародний журнал

(Випуск 121)

Київ
2025

DOI: https://doi.org/10.31073/mivg202501

Засновник – Інститут водних проблем і меліорації Національної академії аграрних наук України. Свідоцтво про державну реєстрацію – серія КВ № 24001-13841Р. Ідентифікатор медіа R30-05221.

Журнал включено до «Переліку наукових фахових видань України» (категорія «Б») за спеціальностями: 201 – Агрономія, 208 – Агроінженерія, 202 – Захист і карантин рослин, 101 – Екологія, 192 – Будівництво та цивільна інженерія, 194 – Гідротехнічне будівництво, водна інженерія та водні технології на підставі наказів Міністерства освіти і науки України № 409 від 17.03.2020 р.; № 320 від 07.04.2022 р. та № 582 від 24.04.2024 р.

У журналі відображено результати теоретичних та експериментальних досліджень із пріоритетних напрямів: агроресурси, водні ресурси, зрошення, осушення, гідрологія, екологія, гідротехніка, агроінженерія тощо. Журнал буде корисним для науковців, фахівців водного та сільського господарства. Два видання журналу за рік публікують оригінальні наукові статті, а також огляди, пов'язані з профілем журналу.

Журнал включено до міжнародних та національних інформаційних і наукометричних баз, репозитаріїв і пошукових систем:

The International System for Agricultural Science and Technology (FAO) – AGRIS

Research Bib Journal Database (Японія) – Academic Resource Index ResearchBib

CrossRef (США) – Crossref

BASE – Bielefeld Academic Search Engine (Німеччина) – BASE

DOAJ (Directory of Open Access Journals) – DOAJ Directory of Open Access Journals

Національна бібліотека України ім. В.І. Вернадського – Національна бібліотека України імені В. І. Вернадського

Open Ukrainian Citation Index (OUCI) (Ukraine) – OUCI

Scientific Indexing Services (США) – SIS Scientific Indexing Services

CIARD RING (Італія) – CIARD RING

Google Scholar (США) – Google Академія

The German Union Catalogue of Serials (ZDB), (Німеччина) – ZDB Zeitschriften Datenbank

Internet Archive (Fatcat) (США)

Пристатейний список літератури продубльовано відповідно до вимог міжнародних систем транслітерації (зокрема наукометричної бази SCOPUS)

Рекомендовано до друку вченою радою Інституту водних проблем і меліорації НААН 02 червня 2025 року (протокол № 10).

Адреса редакції:
Інститут водних проблем і меліорації НААН України
вул. Васильківська, 37, Київ, 03022
Тел. (044) 257-40-30, 067 791 67 11
http://mivg.iwpim.com.ua/index.php/mivg

ISSN 2616-5562 (Online)
ISSN 2616-5643 (Print)

INTERNATIONAL JOURNAL
“LAND RECLAMATION AND WATER MANAGEMENT”

№ 1 • 2025

«МЕЛІОРАЦІЯ І ВОДНЕ ГОСПОДАРСТВО»

KYIV • 2025

МІЖНАРОДНИЙ ЖУРНАЛ

«МЕЛІОРАЦІЯ І ВОДНЕ ГОСПОДАРСТВО»

№ 1 • 2025

"LAND RECLAMATION AND WATER MANAGEMENT"

КИЇВ • 2025

DOI: https://doi.org/10.31073/mivg202501-414
Available at: https://mivg.iwpim.com.ua/index.php/mivg/article/view/414

UDC 631.15:631.62

STATE AND PROSPECTS OF REHABILITATION AND MODERNIZATION OF LAND RECLAMATION SYSTEMS IN MODERN CONDITIONS

M.I. Romashchenko[1], Dr. of Technical Sciences, M.V. Yatsiuk[2], Dr. of Technical Sciences, A.P. Shatkovskyi[3], Dr. of Agricultural Sciences, S.V. Usatyi[4], Ph.D. in Technical Sciences, V.V. Polishchuk[5], Ph.D. in Agricultural Sciences, R.V. Saidak[6], Ph.D. in Agricultural Sciences, S.S. Kolomiets[7], Ph.D. in Agricultural Sciences, L.G. Usata[8], A.S. Sardak[9], Ph.D.

[1] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com;
[2]Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-5535-715X; e-mail: mv_yatsiuk@ukr.net;
[3] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-4366-0397; e-mail: andriy-1804@ukr.net;
[4] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0001-8784-4078; e-mail:s_usatiy@ukr.net ;
[5] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0001-7786-1843; e-mail: vitaliypolishchuk@ukr.net;
[6] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-0213-0496; e-mail:saidak_r@ukr.net;
[7] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-4329-4382; e-mail: kss2006@ukr.net;
[8] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-3265-9024; e-mail: usataya_l@ukr.net;
[9] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-0540-9492; e-mail: anastasiabilobrova1993@gmail.com

Abstract. *Although Ukraine has a modern, scientifically sound, properly enshrined at the legislative and executive levels of the state policy on land reclamation development, the main goal of which is to create an efficient irrigation and drainage sector managed with the participation of water users as the basis for transforming Ukraine into one of the world leaders in food production and export in the context of climate change, the main task of this policy, namely, increasing the area of irrigation and water regulation, is practically not being fulfilled. This is the result of fetishizing the role of the creation of water management organizations and transferring only working irrigation and drainage systems to the ownership of the grassroots level of irrigation and drainage infrastructure. As a result, and due to the lack of a mechanism and sources of VAT payment for the infrastructure transferred to the ownership of the WUCs, the latter are unable to ensure the registration of ownership rights to it and, as a result, to increase the area of irrigation and water regulation by developing and implementing projects for the reconstruction and modernization of this infrastructure, even if they have their own funds for their implementation.*

In addition to the military aggression of the russian federation, the reasons for the stagnation of the process of increasing irrigation and water regulation are also the lack of mechanisms for creating water management companies on non-operational irrigation and drainage systems, financial support through access to medium- and long-term preferential loans for the implementation of irrigation and water regulation works on non-operational irrigation and drainage systems by water management companies, failure to implement the "Action Plan…", first of all, works on inventory, financial, technical and energy audit of existing irrigation and drainage systems, audit of the use of irrigated and drained lands, feasibility studies and projects for the involvement of water resources of the Danube River. Danube River, restoration of the water-regulating and water-storage capacity of Polissya and a number of other tasks without which the full launch of the process of increasing irrigation and water regulation is impossible.

Keywords: *strategy, action plan, long-term plan, irrigation, drainage, water regulation*

Relevance. In the early 90s of the last century, the reclaimed lands of Ukraine occupied almost 6 million hectares, which was 18,6 % of the total arable land, and served as an insurance fund for the state's food supply in years with unfavorable weather conditions. At the same time, irrigated areas amounted to 2,65 million hectares and drained areas to 3,3 million hectares.

In 2017, out of 2,17 million hectares (including the Autonomous Republic of Crimea) of irrigated and 3,2 million hectares of drained land, only 500 thousand hectares (excluding the Autonomous Republic of Crimea) were actually watered, and bilateral water regulation was carried out on an area of less than 250 thousand hectares. hectares, i.e. less than 25 percent of the available irrigation areas and less than 10 percent of the available drainage areas, and reclaimed lands have lost their ability to serve as the state's insurance fund, especially given the significant deterioration in the natural moisture supply of soils due to climate change. That is why in 2019, the Cabinet of Ministers of Ukraine approved the "Strategy of Irrigation and Drainage in Ukraine for the period up to 2030" [1, 2], which aims to increase the actual area of irrigated land to 1,5–1,8 million hectares, to divert excess water in the spring to more than 3 million hectares and to regulate water during the growing season on an area of more than 1 million hectares, and thus create the preconditions for Ukraine's transformation into a globally competitive food producer in the face of climate change.

Therefore, **the purpose of the study** is to comprehensively analyze the current state, prospects and directions of restoration and modernization of land reclamation systems in Ukraine, taking into account climate change and military aggression of the Russian Federation.

Materials and methods of the study. Theoretical methods of scientific research were used: analysis and synthesis, comparison, classification and generalization.

Analysis of recent research and publications. Given the relevance of the study, many scientific works have been devoted to the issue of restoring irrigation and drainage in Ukraine. In particular, Zhovtonog O., Dirksen W., Roest K. [1] assessed the reforms of the irrigation sector in the countries of Central and Eastern Europe, including Ukraine. The scientific substantiation and conceptual foundations for the development of land irrigation in Ukraine are set forth in the works of Romashchenko M.I., Kovalenko P.I., Balyuk S.A. [2, 3]. Romashchenko M.I. and Dekhtyar O.O. [4] worked out the provisions for reforming the water sector of Ukraine in the context of further prospects for the development of irrigation and drainage. Scientists of the Institute of Irrigated Agriculture (Granovska L.M., Pilyarska O.O., 2020) substantiated the legislative regulation of the restoration and development of irrigation in Ukraine [5]. At the same time, as the analysis of scientific publications has shown, scientists have not fully analyzed the reasons for the actual stagnation of the process of increasing irrigation and water regulation in modern conditions.

Research results and their discussion. Unfortunately, neither the adoption of the "Strategy of Irrigation and Drainage in Ukraine for the period up to 2030" [6], the "Action Plan for its implementation…" [7], nor the Law of Ukraine "On the Organization of Water Users and Stimulation of Hydraulic Land Reclamation" [8], nor a number of decisions of the Cabinet of Ministers of Ukraine aimed at separating the functions of formulating and implementing state policies on water resources management and land reclamation and water management and reclamation infrastructure [9–12], have not led to the emergence and development of the process of accelerated development and implementation of investment projects to increase irrigation and water regulation.

Namely, the task of increasing the area of actual irrigation by 1.0–1.2 million hectares, and water regulation by 0.9–1.0 million hectares by 2020. hectares by 2030 was and remains the main target function of the current "Strategy of Irrigation and Drainage in Ukraine for the period up to 2030", and all other tasks, including the task of reforming the system of water resources management and land reclamation, were considered by the developers of the "Strategy…", and all the authors of this article were active, or rather its main developers, as necessary but auxiliary components of the main task. In fact, it was the fulfillment of auxiliary tasks that became the main content of the work in 2020–2024 of the Verkhovna Rada, the Cabinet of Ministers, the central executive bodies of Ukraine (Ministry of Environment, Ministry of Agrarian Policy, State Agency of Water Resources, State Agency of Land Resources), USAID and its contractors. The main result of these works was the development and adoption in 2022 of the Law of Ukraine "On Water Users' Organizations and Stimulation of Hydraulic Reclamation" and a number of bylaws to it [8, 13–16], which initiated the process of creating a new institution in Ukraine – water user organizations (WUOs) with the transfer of on-farm networks with pumping stations and lower-level canals and pipelines belonging to inter-farm networks and owned by the state. In this case, the creation of the WUC was considered as the main driving force (catalyst) for launching the process of increasing the area of actual irrigation and water regulation [8]. In fact, the process of establishing the WUCs turned into a procedure for obtaining and registering their ownership rights to the irrigation and drainage infrastructure transferred to them. And given that the procedure for transferring infrastructure to ownership requires the payment of VAT, and the current owners do not have the funds to pay it, as of 01.06.2025, only 4 of the 62 established WUCs were able to register ownership of the irrigation and drainage infrastructure transferred to them [17], and without this, they are unable to develop and implement projects for its reconstruction and modernization and, accordingly, increase the area of irrigation and water regulation.

It would be appropriate to recall that these complications arose due to the rejection by the working group on the development of the aforementioned Law, primarily by representatives of the Ukrainian Agrarian Council, of the proposal of the IP&M to transfer the infrastructure not to the ownership of the UEC, but to lifetime free use. It is clear that this option excluded the need to pay VAT, as well as to perform a variety of procedures related to the registration of property rights. The proposal of the IP&M to grant the central executive body for the implementation of the state land reclamation policy the right to initiate the creation of WUCs by transferring inoperable on-farm infrastructure to them for use was also not adopted. It was the creation of WUCs on the basis of inoperative but technically suitable on-farm infrastructure that could have become an effective tool for significant increase in irrigation and water management areas through the development and implementation of projects for the reconstruction and modernization of such on-farm networks, but unfortunately, it did not. WUCs continue to be created only on operating irrigation and drainage systems, which can improve their efficiency to some extent, but in principle cannot ensure a significant increase in irrigation and water management areas. Another reason for the stagnation of the process of increasing irrigation areas in the face of the "Strategy of Irrigation and Drainage in Ukraine for the period up to 2030" and the "Action Plan for its implementation…" approved by the Cabinet of Ministers of Ukraine was the failure to fulfill the tasks envisaged by these program documents, primarily the failure to conduct an inventory of existing irrigation and drainage systems, audit the use of reclaimed land as a basis for determining the list and priority of developing feasibility studies and investment projects for the reconstruction and modernization of irrigation and drainage systems based on networked irrigation and drainage systems. Measures are also not being taken to increase water supply for irrigation and water regulation, which is unacceptable in the context of the progressive development of the process of dehydration of the territory of Ukraine as a result of climate change, because the water demand for irrigation and water regulation has increased by at least 30–40 % since the 90s of the last century and continues to grow [18], while the volumes of available surface and groundwater, including for irrigation, are steadily decreasing, primarily in the regions with the greatest need for irrigation and water regulation [19].

That is why both the Strategy and the Action Plan envisaged the development of feasibility studies and projects for the involvement of the Danube River water resources to improve water supply in the southern regions of Ukraine and restore the water storage and water regulation capacity of Polissya. After all, without the implementation of the first project, even with the existence of the Kakhovka Reservoir, there was no possibility of a significant increase in irrigation areas in Odesa, Mykolaiv, Kherson regions and the Autonomous Republic of Crimea, and without the implementation of the second, it is impossible to solve the problem of water regulation in Polissia by implementing projects to reconstruct and modernize the existing drainage systems there, mainly one-way, into drainage-moisturizing or drainage-irrigation systems, just as it is impossible to solve the issue of maintaining the volume of water in the Dnipro reservoirs, which is sufficient to 'The list of unrealized tasks of the "Strategy…" and the "Action Plan…" can be continued, but the general conclusion about the actual state of implementation of work on increasing irrigation and drainage capacity after the adoption of the previously mentioned program documents, as declared by the CM of Ukraine, will remain extremely disappointing – the growth rates of irrigation and water regulation areas unfortunately do not meet the requirements of the time, neither in view of climate change nor in connection with the military aggression of the Russian Federation. This situation is confirmed by the data on actual irrigation areas from 2014 to 2024 (Fig. 1). The choice of the period for analysis was based on the condition of covering the period before the adoption of the Strategy (2014–2019) and after its adoption (2020–2024), as well as after the annexation of the AR of Crimea, so data on irrigation areas in the AR of Crimea and in the partially occupied Donetsk and Luhansk regions were not taken into account in the analysis until 2021 inclusive, and from 2022 only data on irrigation areas in the territories controlled by Ukraine were analyzed.

As shown in Fig. 1, from 2014 to 2020, the actual irrigation area increased by 74 thousand hectares, i.e. only by 15.5 %, and their average annual growth was about 10.6 thousand hectares, or 2 % per year.

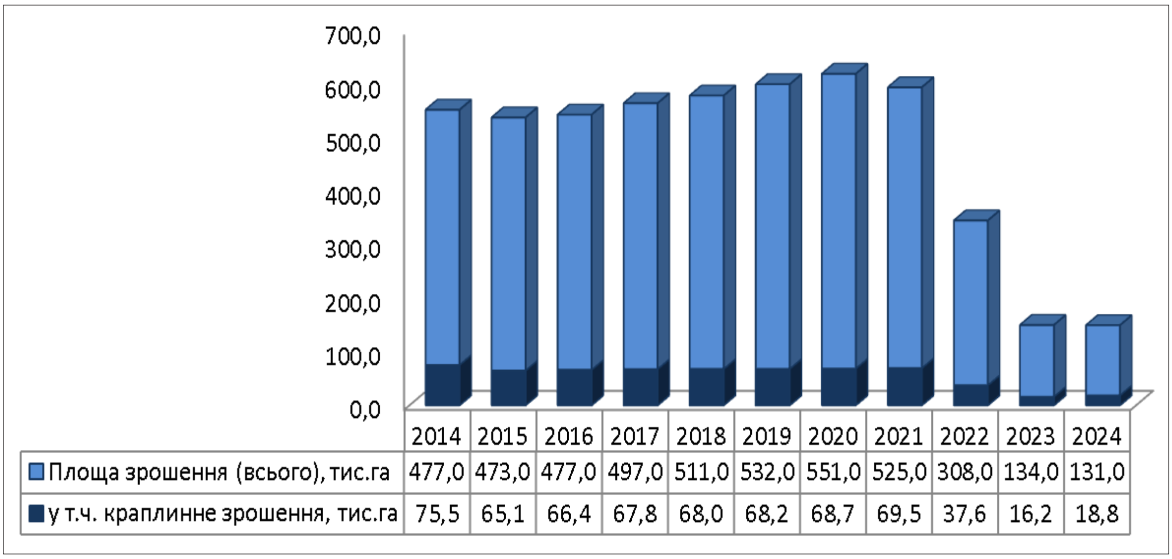


Fig. 1. Actual irrigated areas in 2014–2024

At this rate of increase in irrigation areas, it will take at least 94 years to fulfill the task of the Strategy… to increase irrigation areas by 1.0–1.2 million hectares by 2030, which, of course, cannot be considered acceptable given the progressive increase in the need for irrigation due to climate change. Unfortunately, in 2021, for unknown reasons, the irrigated area not only did not increase, but, on the contrary, decreased by 26 thousand hectares compared to the previous 2020. Subsequently, this process significantly accelerated due to the military aggression of the Russian Federation – from 2022 to 2024, the area of actual irrigation in the territories controlled by Ukraine decreased to 131 thousand hectares (Table 1) according to the State Water Agency.

Table 1. Information on the area of irrigated and drained land as of 01.01.2025 (for 2024)

Code according to the codifier of administrative-territorial units and territories of territorial communities	Region	Total area of irrigated land, thousand hectares	Irrigated thousand hectares (actually)		Total area of drained lands, thousand hectares
			Total	including from state water distribution points	
1	2	3	4	5	6
UA05000000000010236	Vinnytsia	23,8	2,9	2,9	57,3
UA07000000000024379	Volynska	–	–	–	416,6
UA12000000000090473	Dnipropetrovska	198,7	20,1	19,1	–
UA14000000000091971	Donetsk	82,3	0,11	–	4,3
UA18000000000041385	Zhytomyrska	–	–	–	425,4
UA21000000000011690	Transcarpathian	0,9	–	–	183,7
UA23000000000064947	Zaporizhzhya	241,0	–	–	–
UA26000000000069363	Ivano-Frankivsk	–	–	–	192,8
UA32000000000030281	Kyiv	43,9	11,5	11,2	161,4
UA35000000000016081	Kirovogradskaya	40,7	–	–	–
UA44000000000018893	Luhansk	22,8	–	–	11,0
UA46000000000026241	Lviv	–	–	–	513,2
UA48000000000039575	Mykolaivska	190,3	16,5	16,6	–
UA51000000000030770	Odesa	226,9	40,1	39,4	4,4
UA53000000000028050	Poltava	50,8	6,6	6,6	37,2
UA56000000000066151	Rivne	–	–	–	390,4

Continuation of Table 1

1	2	3	4	5	6
UA59000000000057109	Sumy	–	–	–	106,6
UA61000000000060328	Ternopilska	–	–	–	165,5
UA63000000000041885	Kharkivska	82,4	1,7	1,2	11,8
UA65000000000030969	Kherson	427,1	–	–	–
UA68000000000099709	Khmelnytska	–	–	–	117,4
UA71000000000010357	Cherkassy	63,2	32,1	23	55,7
UA73000000000044923	Chernivtsi	–	–	–	121,8
UA74000000000025378	Chernihivska	–	–	–	299,8
TOTAL		1694,8	131,61	120,0	3276,3

Thus, the data of Fig. 1 and Table 1 confirm the previously stated statement that neither the adoption of the “Strategy…”, nor the “Action Plan…”, nor the Law of Ukraine “On Water Users’ Organizations…”, nor the creation of WUCs themselves caused a significant acceleration of the process of increasing irrigation areas (actual irrigation) in 2020–2024. Moreover, this process did not accelerate even after the loss of the majority (over 70 %) of the existing irrigation infrastructure and actual irrigation areas due to their temporary occupation by the Russian Federation and the destruction of the Kakhovka reservoir, which served as a source of water for a significant part of irrigation systems in the Ukrainian-controlled territories of Dnipropetrovs’k, Kherson and Mykolaiv regions. Namely, the accelerated expansion of irrigation areas in the territories controlled by Ukraine and especially water regulation in the Polissya region could and should have played the role of compensating for the loss of crop production due to the military aggression of the Russian Federation and help minimize the negative impact of this process on Ukraine’s export opportunities. Concluding the review of the current state of development of irrigation and drainage, it is necessary not only to emphasize, but to shout out loud that despite the existence of a huge need to increase the area of irrigation and water regulation due to a significant deterioration in the conditions of natural soil moisture supply and, accordingly, the conditions for growing crops throughout almost the entire territory of Ukraine as a result of climate change, as well as due to the loss of almost 20 % of agricultural land and more than 70 % of irrigated land and areas of actual irrigation and due to their temporary occupation by the Russian Federation, on the one hand, there is no need to increase the area of irrigation and drainage, on the other hand, to increase the number of crops grown in Ukraine. In these conditions, having only 131 thousand hectares of actual irrigation (0.6 % of the arable land controlled by Ukraine), which is how much was watered in 2023–2024 in the territories controlled by Ukraine, and about 200 thousand hectares of water regulation (the same 0.6 %). hectares of water regulation (the same 0.6 %, but already of the available area of drained land) in the Polissya zone is to actually recognize the absence of a land reclamation complex in Ukraine that can influence the sustainability of farming and increase the volume of crop production in the context of climate change and military aggression by Russia. This situation, of course, does not suit anyone.

That is why in 2025, the Cabinet of Ministers of Ukraine made another attempt to intensify the process of increasing irrigation areas by adopting another program document, namely the Long-term Plan for the Development of the Irrigation Complex of Ukraine until 2050 [22]. In this context, the Long-Term Plan is presented as one of the components of the reforms developed to implement the European Union’s Ukraine Facility initiative, introduced by Regulation (EU) No. 2024/792 of the European Parliament and of the Council of 29.02.2024.

It is based on the same basic principles as the “Strategy…”, namely:

1. Ensuring food security – stable water supply.
2. Adaptation to climate change.
3. Rational use of water resources.
4. Environmental protection.
5. Economic stability of agriculture.
6. Reducing dependence on food imports, which enhances food security.

The Long-Term Plan (hereinafter referred to as the Plan) has also undergone a strategic environmental assessment in accordance with the Law of Ukraine “On Strategic Environmental Assessment”.

Its main goal, similar to the Strategy…, is to create an efficient irrigation sector, managed with the participation of water users, as a basis for transforming Ukraine into one of the world's leaders in food production and exports in the face of climate change.

According to the Plan's developers, achieving this status by the irrigation sector requires technical and technological modernization of the engineering infrastructure of existing and construction of new irrigation systems, completion of institutional reform of the sector based on involvement of water users in infrastructure management, improvement of existing and development of new legislative and regulatory support, introduction of the latest energy-, resource-saving and environmentally friendly irrigation equipment and technologies, information systems, and other measures.

The main goal of the Long-Term Plan is expected to be achieved through the implementation of strategic objectives, which, again, are fully in line with those of the "Strategy…":

1. Completion of the institutional reform of the irrigation infrastructure management system through the creation of organizations of water users and operators of state-owned irrigation infrastructure management.
2. Stimulating investments in the restoration, modernization and development of existing and construction of new irrigation and water storage infrastructure through the development and implementation of appropriate financing mechanisms from the state and other sources for clearly defined priority programs and projects.
3. Developing and implementing irrigation sector management policies in the interests of viable water user organizations and ensuring their participation in management on the basis of public-private partnerships.
4. Capacity development of organizations that provide scientific substantiation, design, training in the operation and maintenance of irrigation systems.
5. Prioritizing environmental protection, including the preservation and restoration of soil fertility, achieving and maintaining good water resources in accordance with river basin management plans.
6. Creation of geospatial data on the assessment of prospective irrigation areas, availability and accessibility of water resources for irrigation, availability and technical condition of irrigation infrastructure and other parameters necessary for irrigation planning and design of irrigation systems.
7. Formation of a list of priority projects for the reconstruction, modernization and construction of new irrigation systems based on an inventory and assessment of the technical condition of existing irrigation infrastructure and water resources available for irrigation.

Summarizing the main provisions of the Long-Term Plan for the Restoration of the Irrigation Complex of Ukraine until 2050 [22], we would like to emphasize not only the coincidence of its main components with the current "Strategy…" and "Action Plan for its Implementation", but also a number of differences, which, in our opinion, unreasonably limit the scope of the Plan to irrigation systems, leaving drainage systems out of the picture. In our opinion, under the conditions prevailing in Ukraine as a result of climate change and Russian military aggression, the task of accelerated and, preferably, faster restoration of the water regulating capacity of drainage systems in the Polissya region should be a priority at the current stage of development of the reclamation complex of Ukraine. The reorientation to the priority of increasing the area of water regulation in the Polissya zone is due to the specificity of the impact of climate change on the conditions of crop cultivation in different natural and climatic zones of Ukraine, As a result, the Polissia zone has become the most favorable for growing crops that were not previously typical for it, and are also highly profitable and export-oriented, namely corn, sunflower, soybeans, winter wheat, barley and rapeseed, a number of berry (blueberries, raspberries, strawberries) and vegetable crops. The Polissya zone is most favorable due to better natural moisture supply conditions compared to the Steppe and Forest-Steppe zones (average annual precipitation is 600–700 mm), so maintaining the optimal soil water regime for the fullest use of the productivity potential of crop varieties and hybrids grown here can be ensured by using the smallest amounts of water for water regulation or irrigation, or both, and, accordingly, at lower financial costs for water regulation and/or irrigation. Another important argument in favor of accelerating work on increasing the area of water regulation in the Polissia region by developing and implementing projects for the reconstruction and modernization of various types of drainage systems (drainage, drainage-moistening, polder, water recycling) into drainage-moistening, drainage-irrigation, or drainage-moistening-irrigation systems is that excessive precipitation falling in the autumn-winter-early spring periods directly on the water management territories can be used for water regulation by accumulating it in the soils of the aeration zone, drainage channels and special water storage tanks or pools, which are arranged in case of insufficient volumes of water accumulated in the soils of the aeration zone and drainage channels for water regulation during the entire growing season. The accelerated expansion of water regulation areas is also supported by the much greater potential of drainage systems that can be reconstructed or modernized compared to irrigation (3,2 million hectares compared to 0,75–0,77 million hectares of irrigation systems statistically recorded in the territories controlled by Ukraine, Table 1).

’In addition to the fact that the area of irrigation systems that can be used to implement projects for their reconstruction and modernization is extremely small in the territories controlled by Ukraine (Table 1), irrigation can actually be restored on much smaller areas (1,3 to 1,4 times) due to the lack of sufficient water for irrigation on previously planned areas due to increased water demand as a result of climate change. Odesa (over 170 thousand hectares), Cherkasy (about 30,0 thousand hectares), Kirovohrad (over 25 thousand hectares), Poltava (over 20 thousand hectares), and Kyiv (over 15 thousand hectares) regions have the greatest potential for restoring irrigation in the unoccupied territories (Table 1).

In this case, the restoration and development of irrigation in Odesa region will depend on the possibility of attracting water resources from the Danube River. The involvement of the Danube River water resources in the implementation of projects to restore existing irrigation systems in Odesa Oblast to the design irrigation areas, as well as the design and construction of new irrigation systems based on the supply of Danube water to the northwestern and northern districts of Odesa Oblast, will not only not worsen the water and environmental situation, but will also contribute to its significant improvement, especially in currently waterless areas, including by creating favorable conditions for the livelihoods of the population and minimizing the negative impact of climate change. Implementation of irrigation restoration projects in other regions controlled by Ukraine, namely, these irrigation restoration works should be carried out in the first stage (2025–2030) of the implementation of the Long-term Plan for the Development of the Irrigation Complex of Ukraine, will also require solving the issue of providing these projects with sufficient water resources. Therefore, their development should be preceded by work on developing a feasibility study for providing projects with water resources. Given the low natural availability of own water resources in most regions of potential irrigation development, the development of feasibility studies should consider options for using not only surface and/or groundwater, but also wastewater (if available).

But, unfortunately, due to the destruction of the Kakhovka reservoir and the occupation of 20 % of agricultural land and more than 70 % of the available potential of irrigation systems by Russia, as well as the lack of sufficient water resources for a significant increase in irrigation areas in the territories controlled by Ukraine (with the exception of water resources of the ’Danube, the involvement of which is postponed indefinitely due to the failure to fulfill the task of developing a feasibility study and a project for the involvement of water resources of the Danube River in 2022–2025 as envisaged by the Action Plan. ’Danube River to improve the water supply of the southern regions of Ukraine, including for the needs of irrigation development), it is impossible to solve the problem of not only preserving but also increasing the volume of crop production in the context of climate change only by restoring irrigation, as provided for in the Long-term Plan for the Development of the Irrigation Complex. Therefore, the fulfillment of the objectives of the “Strategy…” to increase the area of water regulation in the Polissya region by developing and implementing projects for the reconstruction and modernization of existing drainage systems, as noted above, should not only complement the work on the restoration of irrigation, but also become a major component of the development of the reclamation complex of Ukraine at the present stage.

First of all, the inventory should determine a list of drainage and drainage-moisturizing systems in Chernihiv, Kyiv, Zhytomyr, Rivne, Volyn, and Ivano-Frankivsk oblasts, for which projects should be developed for their reconstruction to supplement/restore their ability to perform water regulation functions throughout the growing season. At the first stage (by 2030), it is necessary to restore the operation of existing drainage systems in a dual-regulation mode on a total area of at least 350 thousand hectares. The restoration and development of drainage systems will not only make it possible to fully utilize the favorable conditions created here due to climate change for growing export-oriented crops (winter wheat, barley, rapeseed, corn, soybeans, sunflower, etc.), It will also help improve the water and environmental situation in the region by stopping unregulated discharges of excess water in the spring, thereby creating conditions to prevent overdrying of soils in summer and the development of dust storms in areas with predominantly mineral soils and soil fires in areas with prevalent peat soils, which were previously not typical for this zone. Therefore, the sooner the implementation of projects to restore drainage systems by reconstructing them into dual-regulation or drainage and irrigation systems, the sooner the preconditions will be created for the transformation of the Polissia zone into a zone of guaranteed (sustainable), cost-effective, and environmentally friendly farming on drained (drained) lands, while restoring the water-regulating and water-storage capacity of this region and returning it to the role of an accumulator of Ukraine's water resources.

But the work on developing projects for the reconstruction and modernization of drainage and irrigation systems, as envisaged by the "Action Plan…", should be preceded by their inventory and audit of the use of existing irrigated and drained lands, which should determine the list and priority of development of projects for the reconstruction and modernization of irrigation and drainage systems, as well as the early development of a feasibility study and a project for the restoration of water regulation and water storage capacity of Polissya, the development of which was not unreasonably delayed during 2022–2025, despite the presence of this task in the "Action Plan…". The results of the inventory and audit should also form the basis for proposals for the creation of an ACC on the basis of irrigation or drainage infrastructure that is not currently used for irrigation or water regulation, but whose technical condition allows it to be used as a basis for the restoration of irrigation or water regulation through the development and implementation of projects for its reconstruction and modernization.

When implementing the tasks of both the Strategy… and the Long-Term Plan…, special attention should be paid to their scientific substantiation and scientific support. First and foremost, scientific institutions of the National Academy of Sciences and the National Academy of Agrarian Sciences should be involved in their implementation, which will allow to reach a qualitatively new technical and technological level of the state of engineering infrastructure, to introduce the latest technical solutions and approaches in the process of managing the irrigation complex of Ukraine.

Scientific substantiation and support will primarily be required for measures to implement the basic principles of the "Strategy…" and "Long-term plan…", namely

• determination of the critical role of irrigation and water regulation in ensuring food security of the state in the context of climate change, military aggression of the Russian Federation and post-war reconstruction;

• formation of principles for managing irrigation and drainage hydraulic infrastructure as a single technologically integrated system;

• formulation of principles of water resources management in land reclamation;

• formation of tariffs for irrigation and water regulation services;

• development of feasibility studies, formulation of technical specifications for the reconstruction and modernization of irrigation and drainage systems in the part:

– application of the latest methods of irrigation and water regulation, namely drip irrigation, including its subsoil type, low-pressure and low-intensity sprinkling, drainage-moisturizing and drainage-irrigation systems, compensatory modes of irrigation and water regulation, and pulse water supply;

– modernization and reconstruction of pumping stations based on the use of pumps with adjustable modes of water supply/discharge, equipping pumping stations with mainly automatic water metering devices;

– use of closed-type networks for water supply/discharge using mainly polymer pipes;

– Implementation of anti-filtration measures in canals and reservoirs/ponds;

– use of alternative and renewable energy sources;

– equipping irrigation systems with the means of preparing and applying ameliorants, fertilizers, trace elements, pest and weed control agents together with irrigation water;

A new scientific, technical and technological level and organizational and legal framework for managing the irrigation and drainage complex will make it possible to turn irrigation and water regulation not only into a highly effective means of increasing crop productivity in the face of climate change, but also into an effective factor in preserving and restoring the fertility of irrigated and drained soils, creating ecologically balanced and sustainable agricultural landscapes. In addition, in the context of climate change, land reclamation systems are also becoming a crucial component of creating favorable conditions for the livelihoods of the rural population and rural development.

Projects for the reconstruction and modernization of existing irrigation and drainage systems should be developed based on the results of their inventory, technical, energy and financial audits and provide for the restoration of irrigation or water regulation in areas sufficient to ensure the transfer of financing for the operation of the restored irrigation/drainage systems to self-sufficiency through the introduction of tariffs for water supply/discharge for irrigation/water regulation needs. At the same time, the size of tariffs should not exceed their economically acceptable level for agricultural producers.

Regarding the economic efficiency of implementing measures to restore and develop both irrigation and drainage systems, numerous studies by various NAAS institutions [19, 23, 24] have clearly proven the high efficiency of growing various crops with a profit of 700 to 1200–1500 USD per hectare. USD per hectare of irrigated and drained land. Also, studies and calculations have shown that at this level of profitability of growing crops under irrigation or water regulation, it is possible to implement projects to restore irrigation and drainage systems with a payback period of no more than 8–10 years.

Conclusions. Despite the existence in Ukraine of a modern, scientifically based, properly enshrined at the legislative and executive levels, state policy on land reclamation development, the main purpose of which is to create an effective irrigation and drainage sector managed with the participation of water users as the basis for Ukraine's transformation into one of the world leaders in food production and export in the face of climate change, the main task of this policy, namely the increase in irrigation and water regulation, is practically not being fulfilled. This is a result of the fetishization of the role of the creation of water management organizations and the transfer of only working irrigation and drainage systems to the ownership of the grassroots (the so-called last mile) of irrigation and drainage infrastructure. As a result, and due to the lack of a mechanism and sources of VAT payment for the infrastructure transferred to, the latter are unable to ensure the registration of property rights to it and, as a result, to increase the area of irrigation and water management by developing and implementing projects for the reconstruction and modernization of this infrastructure, even if they have their own funds for their implementation.

In addition to the military aggression of the Russian Federation, the reasons for the stagnation of the process of increasing irrigation and water regulation are also the lack of mechanisms for creating WUCs on non-operational irrigation and drainage systems, financial support through access to medium- and long-term soft loans for WUCs to restore irrigation and water regulation on non-operational irrigation and drainage systems, failure to implement the "Action Plan…", first of all, works on inventory, financial, technical and energy audit of existing irrigation and drainage systems, audit of the use of irrigated and drained lands, feasibility studies and projects for the involvement of water resources of the Danube River. Danube River, restoration of the water-regulating and water-storage capacity of Polissya, and a number of other tasks without which it is impossible to fully launch the process of increasing irrigation and water regulation.

It is proposed to intensify this process in order to preserve Ukraine's role in solving the world food problem in the context of climate change and military aggression of the Russian Federation by accelerating the development and implementation of projects for the reconstruction and modernization of non-working drainage systems in the Polissya area and irrigation in the territories controlled by Ukraine and unconditional and timely implementation of the entire range of measures provided for by the "Strategy…", "Action Plan…" and "Long-term Plan…".

References

1. Zhovtonog, O., Dirksen, W., & Roest, K. (2003). Comparative Assesment of Irrigation Sector Reform in Central and Eastern European Countries of transition. *Irrigation and Drainage*, 54 (5), 487–500. DOI: 10.1002/ird.208.

2. Kovalenko, P.I. (2011). Aktualni problemy vykorystannia vodnykh resursiv i meliorovanykh zemel na suchasnomu etapi [Actual problems of water resources use and reclaimed lands at the present stage]. *Melioratsiia i vodne hospodarstvo*, 99, 5–16 [in Ukrainian].

3. Romashchenko, M.I. (2013). Kontseptualni zasady vidnovlennia zroshennia u Pivdennomu rehioni Ukrainy [Conceptual foundations for the restoration of irrigation in the southern region of Ukraine]. *Melioratsiya ta vodne hospodarstvo*, 100, 7–17 [in Ukrainian].

4. Romashchenko, M.I., & Dekhtiar, O.O. (2016). Deiaki pytannia reformuvannia vodohospodarskoi haluzi Ukrainy [Some issues of reforming the water sector of Ukraine]. *Melioratsiia i vodne hospodarstvo*, 103, 3–8 [in Ukrainian].

5. Hranovska L.M., & Piliarska O.O. (2020). Zakonodavche vrehuliuvannia vidnovlennia ta rozvytku zroshennia v Ukraini [Legislative regulation of the restoration and development of irrigation in Ukraine]. *Zroshuvane zemlerobstvo*, 74, 28–38. Retrieved from: https://doi.org/10.32848/0135-2369.2020.74.3 [in Ukrainian].

6. Cabinet of Ministers of Ukraine. (2019). Stratehiia zroshennia ta drenazhu v Ukraini na period do 2030 roku [Irrigation and drainage strategy in Ukraine until 2030]. Order of the Cabinet of Ministers

of Ukraine No. 688-r (Aug. 14, 2019). Uriadovyi kurier, 170. Retrieved from: https://zakon.rada.gov.ua/laws/show/688-2019-%D1%80 [in Ukrainian].

7. Cabinet of Ministers of Ukraine. (2020). Plan zakhodiv z realizatsii Strategii zroshennia ta drenazhu v Ukraini № 1567-r [Action plan for the implementation of the Irrigation and Drainage Strategy in Ukraine]. *Government courier*, 250. Retrieved from: https://zakon.rada.gov.ua/laws/show/1567-2020-%D1%80#Text [in Ukrainian].

8. Zakon Ukrainy Pro organizatciyu vodokorystuvachiv ta stimuluvannia gidrotekhnichnoi melioratsyi zemel [On the organization of water users and stimulation of hydrotechnical land reclamation]. (2022). Pryiniatyi 17 lutogo 2022 № 2079-IX. *Holos Ukrayiny*, 98. Retrieved from: https://zakon.rada.gov.ua/laws/card/2079-20 [in Ukrainian].

9. Cabinet of Ministers of Ukraine. (2015). Pro Derzhavne ahentstvo rozvytku melioratsii, rybnoho hospodarstva ta prodovolchykh prohram [About the State Agency for the Development of Land Reclamation, Fisheries and Food Programs]. Postanova Kabinetu Ministriv Ukrainy, № 895 (Sept. 30, 2015). *Government courier*, 215. Retrieved from: https://zakon.rada.gov.ua/laws/show/895-2015-%D0%BF#Text [in Ukrainian].

10. Cabinet of Ministers of Ukraine. (2021). Deiaki pytannia rozpodilu okremykh povnovazhen tsentralnykh orhaniv vykonavchoi vlady u sferi melioratsii zemel [Some issues of the distribution of certain powers of central executive bodies in the field of land reclamation]. Postanova KM Ukrainy № 539 (24 May 2021). *Government courier*, 102. Retrieved from: https://zakon.rada.gov.ua/laws/show/539-2021-%D0%BF#Text [in Ukrainian].

11. Cabinet of Ministers of Ukraine. (2022). Pro peredachu tsilisnykh mainovykh kompleksiv derzhavnykh pidpryiemstv, ustanov ta orhanizatsii do sfery upravlinnia Derzhavnoho ahentstva rozvytku melioratsii, rybnoho hospodarstva ta prodovolchykh prohram [On the transfer of integral property complexes of state enterprises, institutions and organizations to the sphere of management of the State Agency for the Development of Land Reclamation, Fisheries and Food Programs]. Resolution of the Cabinet of Ministers of Ukraine No. 714-r. (August 12, 2022), Government courier, 183. Retrieved from: https://zakon.rada.gov.ua/laws/show/714-2022-%D1%80#Text [in Ukrainian].

12. Cabinet of Ministers of Ukraine. (2022). On Amendments to Certain Acts of the Cabinet of Ministers of Ukraine on Stimulating Land Reclamation [On Amendments to Certain Acts of the Cabinet of Ministers of Ukraine on Stimulating Land Reclamation]. Postanova Kabinetu Ministriv Ukrainy № 1077 (Sept. 27, 2022). *Government courier*, 213. Retrieved from: https://zakon.rada.gov.ua/laws/show/1077-2022-%D0%BF#Text[in Ukrainian].

13. Kabinet Ministriv Ukrainy (2022). Pro zatverdzhennia modelnoho statutu orhanizatsii vodokorystuvachiv [On approval of the model charter of the water users' organization]: Postanova Kabinetu Ministriv Ukrainy № 962 (August 27, 2022). *Government courier*, 189. Retrieved from: https://zakon.rada.gov.ua/laws/show/962-2022-%D0%BF#Text [in Ukrainian].

14. USAID. (2023). Posibnyk z pytan utvorennia ta diialnosti orhanizatsii vodokorystuvachiv [Manual on the formation and activities of water user organizations.]. *USAID Office for International Development*, 176 [in Ukrainian].

15. Draft Law on the introduction of a zmin to deyaky zakonodavchykh acts in order to improve the system of upravlennya of the executive infrastructure of the municipal system of state power from July 21, 2022, No. 7577. Retrieved from: https://itd.rada.gov.ua/billInfo/Bills/Card/40049 [in Ukrainian].

16. Proekt Zakonu Ukrayiny. (2021). On amendments to Article 133 of the Tax Code of Ukraine regarding the features of the non-profit status of water user organizations [On amendments to Article 133 of the Tax Code of Ukraine regarding the features of the non-profit status of water user organizations]. Vid 04.03.2021 № 5203. Retrieved from: https://w1.c1.rada.gov.ua/pls/zweb2/webproc4_1?id=&pf3511=71308 [in Ukrainian].

17. Orhanizatsiyi vodokorystuvachiv [Water user organizations] Retrieved from: https://darg.gov.ua/_melioracija_zemelj_0_1075_menu_0_1.html; https://docs.google.com/spreadsheets/d/1TOmuUl0G7g_HR779AIS0_TA3nd6bNT0D/edit?gid=1070588612#gid=1070588612 [in Ukrainian].

18. Scientific principles of development of the agricultural sector of the economy of the Southern region of Ukraine (2017) / NAAN Ukrayiny; under the scientific editorship of M: M. I. Romashchenka, R. A. Vozhehovoyi, A. P. Shatkovs'koho. Kherson: Oldi-plyus, 438 s [in Ukrainian].

19. Romashchenko, M., Saydak, R., Matyash, T., & Yatsyuk, M. (2021). Irrigation efficiency depending on water consumption [Irrigation efficiency depending on water consumption]. *Melioratsiya ta vodne hospodarstvo*, (2), 150–159. DOI: https://doi.org/10.31073/mivg202102-308 [in Ukrainian].

20. Usatyy, S.V., Romashchenko, M.I., & Polishchuk, V.V. (2024). Restoration of irrigation in Ukraine under martial law [Restoration of irrigation in Ukraine under martial law]: Materialy mizhnarodnoy naukovo-praktychnoy konferentsiyi "Voda dlya myru" [Water for the Future], prysvyachenoy Vsesvitn'omu dnyu vodnykh resursiv (21 bereznya 2024, Kyyiv). Kyyiv: IVPiM, 90–91. Retrieved from: http://waterday.iwpim.com.ua/Water_day_tezy2024.pdf DOI: https://doi.org/10.31073/mivg2024 [in Ukrainian].

21. Romashchenko, M.I., Yatsyuk, M.V., Shatkovs'kyy, A.P., Usatyy, S.V., Polishchuk, V.V., & Saydak, R.V. (2025). Perspektyvy vidnovlennya zroshennya ta drenazhu v Ukrayini v umovakh voyennoho stanu [Prospects for the restoration of irrigation and drainage in Ukraine under martial law]. *Voda dlya maybutn'oho: upravlinnya, zberezhennya, innovatsiyi*: XIII Mizhnarodnf naukovo-praktichna konferentsiya. Kyiv: Instytut vodnykh problem i melioratsiyi NAAN, 239–241. DOI: https://doi.org/10.31073/mivg2025 [in Ukrainian].

22. Cabinet of Ministers of Ukraine. (2025). Long-term plan for the development of the irrigation complex of Ukraine until 2050 [Long-term plan for the development of the irrigation complex of Ukraine until 2050]. Approved by the Cabinet of Ministers of Ukraine (25 March, 2025), No. 280-r. Retrieved from: https://www.kmu.gov.ua/npas/pro-zatverdzhennia-dovhostrokovoho-planu-rozvytku-iryhatsiinoho-kompleksu-ukrainy-do-2050-roku-280r-250325 [in Ukrainian].

23. Usatyi, S., Romashchenko, M., Polishchuk, V., & Usata, L. (2024). The Methodology of Technical and Economic Justification for the Construction of Irrigation Systems to Prevent and Reduce Risks in Agriculture. Book chapter in book "Sustainable Soil and Water Management Practices for Agricultural Security". IGI Global. Chapter 11, 277-314 DOI: 10.4018/979-8-3693-8307-0.ch011

24. Romashchenko, M., Faybishenko, B., Onopriienko, D., Hapich, H., Novitskyi, R., Dent, D., Saidak, R., Usatyi, S., & Roubik, H. (2025). *Prospects for restoration of Ukraine's irrigation system Water International*. 1–17. DOI: https://doi.org/10.1080/02508060.2025.2472718

УДК 631.15:631.62

СТАН І ПЕРСПЕКТИВИ ВІДНОВЛЕННЯ ТА МОДЕРНІЗАЦІЇ МЕЛІОРАТИВНИХ СИСТЕМ В СУЧАСНИХ УМОВАХ

М.І. Ромащенко[1], докт. техн. наук, М.В. Яцюк[2], докт. техн. наук, А.П. Шатковський[3], докт. с-г. наук, С.В. Усатий[4], канд. тех. наук, В.В. Поліщук[5], канд. с.-г. наук, Р.В. Сайдак[6], канд. с.-г. наук, С.С. Коломієць[7], канд. с.-г. наук, Л.Г. Усата[8], А.С. Сардак[9], доктор філософії

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com;
[2] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-5535-715X; e-mail: mv_yatsiuk@ukr.net;
[3] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-4366-0397; e-mail: andriy-1804@ukr.net;
[4] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0001-8784-4078; e-mail: s_usatiy@ukr.net;
[5] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0001-7786-1843; e-mail: vitaliypolishchuk@ukr.net;
[6] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-0213-0496; e-mail:saidak_r@ukr.net;
[7] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-4329-4382; e-mail: kss2006@ukr.net;
[8] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-3265-9024; e-mail: usataya_l@ukr.net;
[9] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-0540-9492; e-mail: anastasiabilobrova1993@gmail.com

Анотація. *Наявність в Україні сучасної науково обґрунтованої, належним чином закріпленої на законодавчому та виконавчому рівнях державної політики з розвитку меліорації земель, основною метою якої є створення ефективного сектору зрошення та дренажу, керованого за участю водокористувачів, як основи перетворення України на одного із світових лідерів виробництва та експорту продовольства в умовах зміни клімату, головне задання цієї політики, а саме нарощування площ поливу та водорегулювання, практично не виконується. Це стало наслідком фетишизації ролі* *в нарощуванні площ зрошення та водорегулювання процесів створення ОВК та передачі їм у власність низової ланки зрошувальної та дренажної інфраструктури лише працюючих систем зрошення та дренажу . Внаслідок цього, а також через відсутність механізму та джерел сплати ПДВ за інфраструктуру, що передається у власність ОВК, останні не в змозі забезпечити реєстрацію прав власності на неї і, як наслідок, здійснювати нарощування площ зрошення та водорегулювання шляхом розроблення та реалізації проектів з реконструкції та модернізації цієї інфраструктури навіть за наявності власних коштів на їх виконання.*

Причинами стагнації процесу нарощування площ поливу та водорегулювання, окрім військової агресії рф, є також відсутність механізмів створення ОВК на непрацюючих системах зрошення та дренажу, фінансової підтримки через доступ до середньо – та довгострокових пільгових кредитів виконання ОВК робіт з відновлення зрошення та водорегулювання на непрацюючих системах зрошення та дренажу, невиконання передбачених «Планом заходів…», в першу чергу робіт з інвентаризації, фінансового, технічного та енергетичного аудиту наявних систем зрошення та дренажу, аудиту використання зрошуваних та осушуваних земель, ТЕО та проектів залучення водних ресурсів р. Дунай, відновлення водорегулюючої і водоакумулюючої здатності Полісся та ряду інших завдань без виконання яких повноцінний запуск процесу нарощування площ поливу та водорегулювання неможливий.

Ключові слова: *стратегія, план заходів, довгостроковий план, зрошення, дренаж, водорегулювання*

DOI: https://doi.org/10.31073/mivg202501-417
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/417

UDC 631.4: 631.47

SPATIAL AND TEMPORAL CHANGES IN THE ECOLOGICAL AND RECLAMATION STATE OF DRAINLESS AREAS

O.V. Vlasova[1], Dr. of Agricultural Sciences, D.P. Savchuk[2], Ph.D. in Technical Sciences, I.A. Shevchenko[3], Ph.D. in Technical Sciences, A.M. Shevchenko[4], Ph.D. in Agricultural Sciences, O.M. Kozytskyi[5]

[1] Institute of Water Problems and Land Reclamation of the NAAS of Ukraine, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-1911-4329; e-mail: elena_vl2001@ukr.net;
[2] Institute of Water Problems and Land Reclamation of the NAAS of Ukraine, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-7683-6005; e-mail:savchuk_igim@mail.com;
[3] Institute of Water Problems and Land Reclamation of the NAAS of Ukraine, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-7401-8786; e-mail: irashef@ukr.net;
[4] Institute of Water Problems and Land Reclamation of the NAAS of Ukraine, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-2637-6538; e-mail: monitoring_protect@ukr.net;
[5] Institute of Water Problems and Land Reclamation of the NAAS of Ukraine, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-4459-6331; e-mail: olegkoz@ukr.net

Abstract. *The article presents the results of studies of spatial and temporal changes in the ecological and land reclamation status of drainless areas based on the use of high and medium spatial resolution satellite data. The authors assessed the geomorphological, hydrogeological, soil and land reclamation conditions of the steppe zone of Ukraine and noted that heterogeneous natural conditions such as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contributed to the development of processes of harmful effects of water and the nature of their manifestation. A large drainless area, the Petrivskyi depression in the area of the Kakhovka irrigation system, was chosen as the object of study. The processes of land degradation on the territory of the sub were identified by detecting various manifestations of spectral and textural changes in soil and vegetation surfaces under the influence of water and wind erosion, and an unbalanced land use system based on satellite images of various earth surface scanning systems. Changes were identified and studied by vegetation, soil, and water spectral indices, which made it possible to observe the flooding of the territory. Observations were carried out in different years and cover a period of more than 40 years: 1985–2015 – the most active flooding of the territory was observed; 2002, 2003 and 2005 – large-scale winter-spring flooding; 2018–2024 – the absence of a drainage system that is in decline was recorded; 2023, 2024 – the impact of hostilities on the territory of the pad. Based on the results of studies of the spatial differentiation of soil emissions and their temporal dynamics, the authors have developed a complex indicator that is a function of three components – the spectral indices NDVI, NDWI and CM. Verification of the studies of the period 1991–2017 of the averaged values of the spectral indices showed that the closest correlation exists between NDWI and NDVI and is 0,92. The experimental area was analyzed for soil fertility in contrast to the depleted soils of the pudu. It was determined that with the change in humus concentration, the color of the topsoil changes, which in turn causes changes in the spectral characteristics of the satellite image.*

Through long-term observations, the spatial and temporal changes in the ecological and reclamation state of the drainless area and the probability of loss of the functional resource of the reclamation system as a whole were studied.

Keywords: *drainless territories, drainage system, ecological and reclamation state, satellite data, spectral indices, spatial and temporal changes*

Relevance of the research. The restoration of irrigation and drainage, which is a key tool for the development of the agricultural sector of the economy, is emphasized in the current document "Strategy of Irrigation and Drainage in Ukraine for the period up to 2030" [1]. Therefore, first of all, the issue of overcoming the consequences of the war over time and restoring the operation of damaged irrigation and drainage systems that have not lost their resource is acute. To do this, it is necessary to study the operation of the systems in previous years to identify and take into account design flaws, assess their condition, and provide recommendations for future reconstruction and operation.

Without irrigation and drainage in the risky farming zone of the Steppe zone of Ukraine, obtaining stable yields and sustainable development of the agro-industrial complex is virtually impossible [1]. At the same time, out of 924 vertical drainage wells and 119 horizontal drainage pumping stations in the Kherson region, only about 1–15 % were productively operating by 2019. Therefore, this issue should be studied. It is advisable to research and study the operation of irrigation and drainage systems over a long time period using modern technologies in combination with ground observations.

Analysis of previous research and publications. Worldwide experience shows that it is advisable to detect and evaluate the operation of drainage systems using remote sensing [2–4]. In this case, research should be aimed at a comprehensive analysis of applied processes in the spatial localization, classification or assessment of the actual state of subsurface drainage systems using remote sensing methods.

To monitor the state of the drainage system, groundwater levels are usually monitored at pumping stations and hydrogeological observation wells. However, this method helps to observe the state of the system only pointwise or linearly. Therefore, studies on the state of drainage systems should be based on both the analysis of ground-based hydrogeological observations of groundwater levels and their comparison with satellite images [5–9].

Landsat archival satellite images are widely used worldwide to analyze time series of terrain and analyze spatial changes in vegetation around drainage areas [4, 5]. The state of vegetation, as an indicator of biological productivity, is assessed by the normalized difference vegetation index (NDVI) during the peak of the growing season. This approach to assessing the situation based on the use of NDVI [10] is performed during the growing season.

For timely inspection of drainage systems, the modified normalized water index (MNDWI) is used, which is a valuable indicator for monitoring waterlogged lands [11]. The index is calculated using Landsat satellite data (Landsat L8 Oli TIRS, Landsat ETM+, Landsat TM). Remote sensing and GIS technologies are used to determine the location and delineation of existing drainage systems [12]. Drainage is localized using color infrared satellite images. Because the soil directly above the drainage surface dries out faster than the surrounding soil, the reflectivity of the drier soil often shows up in the infrared spectrum.

Prolonged irrigation on the massifs led to regional and localized increases in groundwater levels. The regional rise on the background of irrigation occurred with an annual rise rate of about 0,8 m/year. Localized manifestations of flooding are observed at the bottom of the depression, in the riverbed areas and in the area of sprinklers. The effectiveness of drainage in difficult natural and water management conditions on the main irrigation systems and in a number of settlements in the south of Ukraine is covered in [13–16].

The aim of the work is to study the spatial and temporal changes in the ecological and reclamation state of a drainless area based on long-term satellite data observations and to establish the probability of loss of the functional resource of the drainage system as a whole.

Research methods and materials. In conducting research with satellite data, we used the passive method of remote sensing, analytical analysis of scientific papers, spectral and geospatial analysis, system analysis, ground surveys and experimental studies according to generally accepted and certified methods.

To resist the harmful effects of water in the Kherson region, drainage systems of various types were built on the Kakhovska irrigation system on an area of 45 thousand hectares. The irrigated area is characterized by diverse and complex geomorphological, hydrogeological, and soil-reclamation conditions [8].

Regarding the characteristics of the study area, it should be noted that heterogeneity of natural conditions is a characteristic feature of the Kherson region, and such components of the environment as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contribute to the development of processes of harmful effects of water and determine the nature of their manifestation.

According to the climate zoning, the territory belongs to the steppe Atlantic-continental climate region of the temperate climate zone. The climate is temperate continental, with insufficient moisture, short winters and long hot summers. The climate is formed under the influence of solar radiation and atmospheric circulation, as well as local factors of influence: the proximity of the sea and Lake Syvash. In spring and summer, the effect of solar radiation is manifested in the warming of the earth's surface and the surface layer of the atmosphere.

The study area belongs to the denudation-accumulative forest plain of high riverine and complex terraces with relief forms: drainless areas, saucers, and beams. Drainless territories are shallow (up to 3–5, rarely 10–15 m) enclosed mostly round or oval flat-bottomed areas with an area of hundreds and thousands of square meters. Slightly convex flat pits are clearly defined in the relief. Their diameter is from 0.2 to 3–4 km.

The territory is represented by meadow-dark chestnut gley saline-saline soils and meadow chestnut gley saline-saline soils. The depth of the groundwater table within the drainless area depends on the relief and varies from 0,5 m to 15,0 m.

Among the existing drainage-free areas, the vertical drainage system located within the Petrivskyi depression, which belongs to large asymmetric drainage-free areas with active wind and water erosion, is scientifically noteworthy. Soil erosion is one of the main indicators in a comprehensive assessment of the ecological state of territories. This phenomenon has been studied in the spatial and temporal dimensions using modern methods involving satellite data.

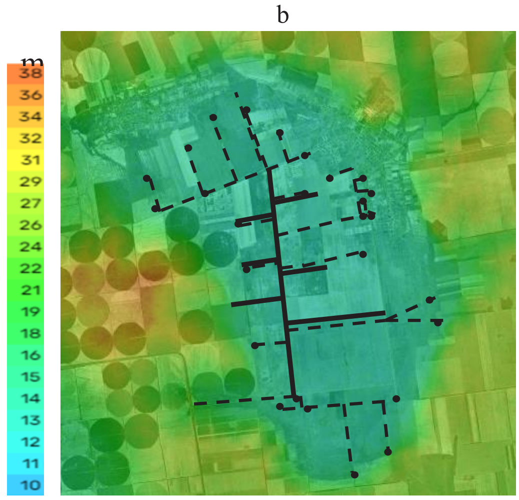
The drainage provides flood protection for the adjacent irrigated area. The catchment area of the pond is more than 30,000 hectares, and the vertical drainage area is 3,190 hectares. The lowest elevation of the bottom of the basin is 12,5 m, and the highest 25,0–30,0 m. On the slopes are agricultural fields that were previously irrigated with modern sprinklers. In the northern part of the pond, the main Kakhovskyi Canal passes through, which affects the groundwater regime.

The location map of the study object was created on the basis of the terrain map available on the Topographic Map of Ukraine website [17], Maxar satellite image (Google Earth Pro) dated 07/14/2021, and the drainage system location scheme (Fig. 1).

Two settlements are located in the central part of the pud – Petrivka and Pavlivka. The area of Pavlivka village is more than 500 hectares, and Petrivka village is 1000 hectares. Their territory has absolute ground surface elevations of mostly 12–20 meters. In the village of Petrivka, a vertical drainage system was built on an area of 190 hectares. The drainage wells are located in the lowest parts of the settlement. The constructed drainage includes 7 wells (Table 1).

It should be noted that vertical drainages protect the territory from flooding on an area of 300, 600, 2100 and 600 hectares.

a b c



d

Fig. 1. The collector-drainage system of the Petrivskyi depression in the area of the Kakhovska irrigation system:

a – terrain map (“Topographic Map of Ukraine” [17]); b – Maxar satellite image (Google Earth Pro geospatial analysis service) dated 14.07.2021; c – drainage system layout; d – integrated image of the terrain, satellite image and drainage system layout

1. Hydrogeological parameters of the aquifer in the areas of vertical drainage within the Petrivskyi depression

Drainage area, ha	Number of wells, pcs.	Water permeability, m^2/day	Filtration coefficient of the upper layer, m/day	Filtration coefficient of the separation layer, m/day	Water return	Mineralization of drainage water, g/l
300	3	240	0,14	0,0030	0,002	1,1–5,2
2100	9	–	–	–		1,1–5,2
600	6	300	0,14	0,0004	0,002	2,0–3,0
190	7	–	–	–	–	–
600	5	–	–	–	–	–
Total 3790	30	–	–	–	–	–

On an area of 300 hectares, two wells protect the village of Petrivka and one protects the village of Pavlivka. Drainage on an area of 600 hectares has a positive impact on flood protection in Pavlivka village. The main part of the drainage is built in the central lowest part of the pond. The drainage area here is 2100 and 600 hectares. The drainage system includes 14 vertical drainage wells, an open drainage channel, a drainage pumping station and a pressure pipeline for drainage from the pit.

The drainage covers the highest areas of the pit. The total drainage area is 3790 hectares. There are 30 vertical wells in the drainage area. The distance between the wells is generally 1–3 km. The depth of the wells is 34 meters. Some wells are 20 meters deep.

The Petrivskyi depression is characterized by a significant saturation of the territory with irrigation systems. Thus, the territory of the sub is intensively used in terms of land reclamation.

Research results and their discussion. Observations were made in different years and generally cover a period of more than 40 years. Thus, during 1985–2015, the most active flooding of the territory was observed, as evidenced by Landsat 2–7 satellite images (Fig. 2).

Regarding the period of large-scale flooding and inundation of the Kherson region in 2005, it is advisable to provide a NOAA, IR (infrared) image as of March 1 (Fig. 3).

The climate change observed in recent decades has caused a sharp increase in average annual air temperatures in Ukraine, especially in its steppe regions [19]. According to observations at the Askania Nova weather station, the current climatic norm for air temperature (1991–2020) is 10,79 °C, which is 0,93 °C higher than the previous climatic norm (1961–1990). A particularly intense increase in air temperature has been observed since 2000. While the average annual temperature averaged 9,79 °C between 1910 and 2000, in the following period its value increased to 11,2 °C, i.e. by 1,41 °C.

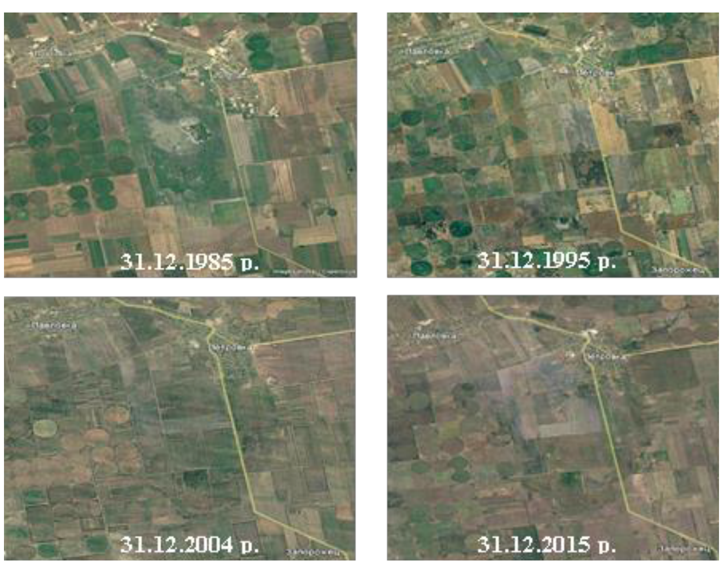


Fig. 2. The territory of the floodplain during the period of active flooding according to the images (Google Earth Pro geospatial analysis service)

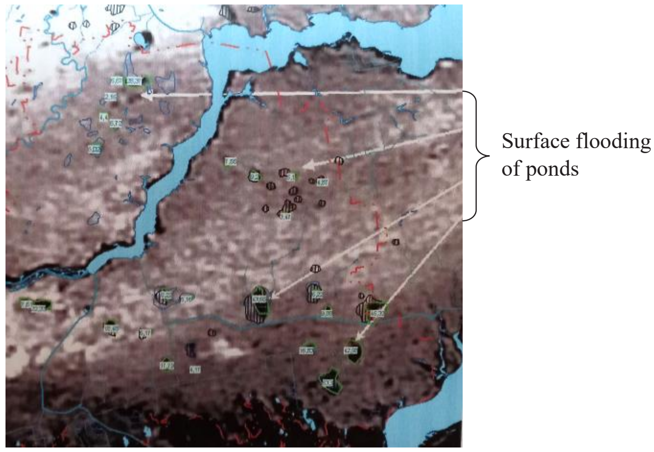


Fig. 3. Territories of the Kherson region affected by flooding and inundation as of March 1, 2005 [18].

The increase in air temperature led to a sharp increase in potential total evaporation, which, according to research [20], increases by 9 % with an increase in temperature by 1 °C. At the same time, an analysis of long-term precipitation observations at the Askania Nova weather station shows that since 1945, their amount has remained almost constant (Fig. 4). The average amount of precipitation over the past 77 years (until 2021) was 401 mm, the previous climatic precipitation rate (1961–1990) was 399 mm, and for the period from 1991 to 2020 it increased to 409 mm. Such an increase in precipitation is not typical for the entire Kherson region, in particular, in Kherson, the climatic precipitation rate decreased by 9 mm.

The highest amount of precipitation is observed in May-July (an average of 44 mm per month), and the lowest in December-March (an average of 28 mm per month). The largest increase in precipitation over the past 30 years compared to the previous climatic norm was recorded in June – by 6.4 mm per month, and the largest decrease – in December, by 7 mm (Fig. 5).

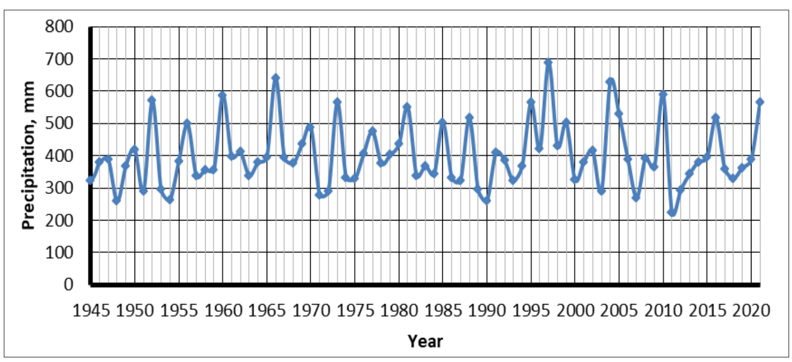


Fig. 4. Long-term precipitation dynamics at Askania Nova weather station

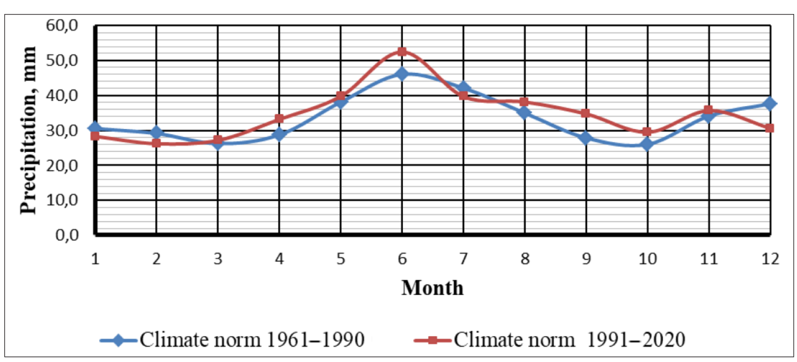


Fig. 5. Intra-annual distribution of precipitation at Askania Nova weather station for different observation periods

The analysis of climatic factors shows that the increase in flooding levels in the floodplain during 1985–2015 is not related to climate change, but is caused by anthropogenic factors, in particular, the deterioration of the drainage system.

Water and wind erosion of the soil in the bed was assessed by a complex indicator containing various spectral indices.

During this period, we used spectral indices calculated on the basis of Landsat satellite images as a comprehensive indicator of the state of the bedrock under water and wind erosion**.**

The periods with more favorable weather conditions were studied separately. For this purpose, the territory of the Petrivskyi depression was surveyed using satellite data in 1991, 2000, 2007, and 2017. The spectral indices CM (clay content in soils), NDVI (vegetation index), and NDWI (moisture index) were calculated based on Landsat images. The experimental area was analyzed for the condition of the soils of the irrigated massif in contrast to the depleted soils of the pond. For this purpose, the sub-floor depression was identified and thematic maps were constructed to record differences in the composition of fertile (irrigated crops) and infertile soils (smoothing of the relief, loosening of soils in the lowlands).

Based on the results of the study of the spatial differentiation of soil emissions and their temporal dynamics, a complex indicator was developed, which is a function of three components: I comp. = *f* (NDVI, NDWI, CM).

The degradation processes were identified by detecting various manifestations of spectral and textural changes in the soil and vegetation surface, which are affected by water and wind erosion, unbalanced land use, etc. It was found that heterogeneous natural conditions such as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contributed to the development of processes of harmful effects of water and determined the nature of their manifestation. The NDVI vegetation index calculated from satellite images made it possible to identify the types of soil degradation that cause a decrease in the concentration of humus in the upper biologically active soil layer.

Maps of the territory's NDVI images for 1991, 2000, and 2007 are shown in Figure 6.

Based on the images from January 13 to June 24, 2003 (NOAA) and decadal SPOT VGT satellite data, a joint graph of the dynamics of changes in the flooded area of the Petrivskyi depression and the vegetation index averaged over the low area was constructed. The period of the greatest flooding occurred on March 16-18, 2003. The territory of the floodplain was surveyed using retrospective satellite data from 1991, 2000, 2006, and 2007, and the most unfavorable climate impact on hydrothermal and agricultural conditions was revealed. Based on the data obtained, the spectral soil indices IO and SM, as well as additional indices, were calculated: NDWI – moisture content for certain subsoil depressions. The dynamics of changes in the average values of the indices is shown in Figure 7.

The study proved that as the humus concentration changes, the color of the topsoil changes, which in turn causes changes in the spectral characteristics of the satellite image. If soil erosion is calculated individually for each pixel, the NDVI and surface slope gradient can be used to calculate the degree of soil erosion per year. Vegetation indices of redness RI and brightness BI and their correlation with ground data and spectral indicators of soil erosion can be used to classify erosion degradation – to determine the extent of planar erosion.

Another indicator of land degradation is the reflectivity of the earth's surface (albedo). If the albedo increases by 6-14 %, the area with this type of soil is classified as unstable, by 15–20 % as a zone with mild degradation, by 21–50 % as moderate degradation, by 51–75 % as severe degradation, and by 76–100 % as extreme degradation.

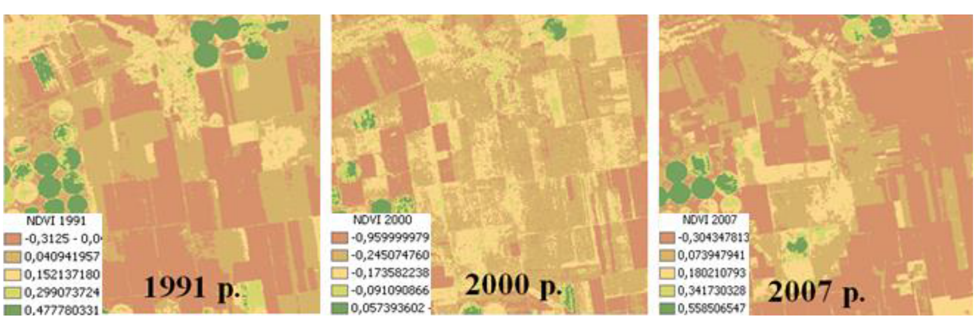


Fig. 6. Maps of NDVI spectral index of the Petrovskyi depression according to research conducted in 1991–2007

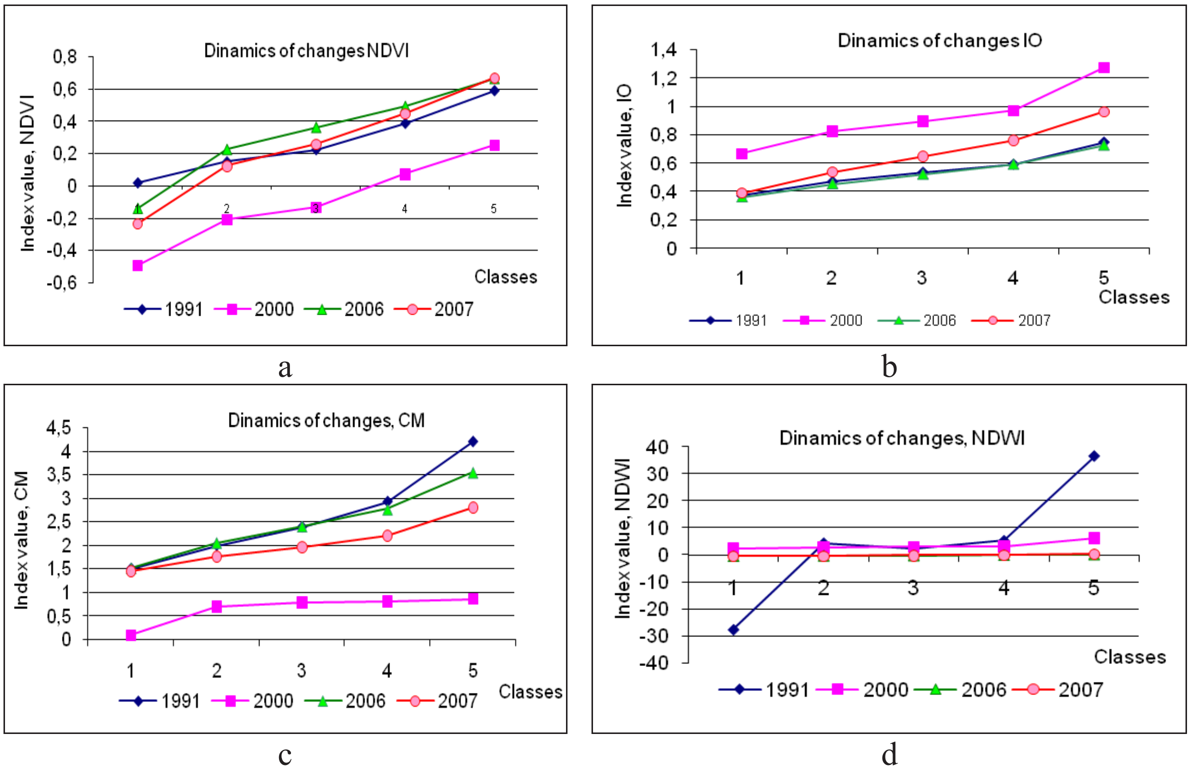


Fig. 7. Diagrams of changes in the averaged values within the Petrivskyi depression according to the 1991–2007 studies:

a – NDVI; b – IO; c – SM; d – NDWI

In further studies conducted in 2017, Landsat 8 image for the month of August was used to identify the study area and calculate the NDVI, IO, CM indices (Fig. 8). Separately, we calculated the humidification by NDWI. The experimental area was analyzed for soil fertility of the irrigated area in contrast to the depleted soils of the subsoil. For this purpose, the subsoil depression was isolated by an isoline (black outline).

The thematic maps show the differences in the composition of fertile (irrigated crops) and infertile soils (smoothing of the relief, loosening of soils in the lowlands).

After completing the studies of the period 1991–2007 and 2017, the results of the averaged values of the spectral indices were verified, which showed that the closest correlation $R^2 = 0,92$ exists between NDWI and NDVI, which is indisputable. A new stage of research was launched in 2018 with the involvement of CNES/Airbus and Maxar Technologies imagery. The involved high-resolution images of the study area are shown in Fig. 9.

The images show a fuzzy blurred image of the bedding even in the summer and autumn, which indicates that the drainage system is not working and is in poor condition.

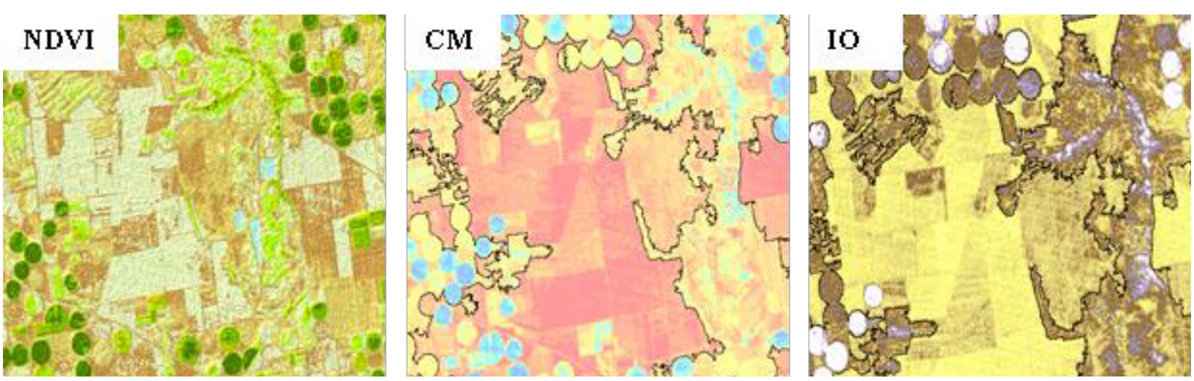


Fig. 8. Maps of the spectral indices of the Petrivskyi depression NDVI, SM, IO for the period of research in 2017

Fig. 9. High-resolution images of the study area by Maxar Technologies and CNES/Airbus

The latest studies of reclaimed land in drainless areas were conducted in 2023–2024 to determine the impact of hostilities on the territory of the depression. For this purpose, Sentinel-2 L2A imagery for 20.06.2023 and 01.01.2024 was used. No changes were detected (Fig. 10).

The combination of healthy vegetation channels SWIR1, Red8, Blue of the Sentinel satellite made it possible to assess the current state of the Petrivskyi depression. The soil structure does not appear to be eroded during the wettest winter period.

Conclusions and further research. It is advisable to identify soil degradation processes by identifying various manifestations of spectral and textural changes in the soil-plant surface, which are affected by water and wind erosion, unbalanced land use, etc.

It has been established that heterogeneous natural conditions such as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contributed to the development of processes of harmful effects of water and determined the nature of their manifestation.

It is determined that with the change in humus concentration, the color of the topsoil changes, which in turn causes changes in the spectral characteristics of the satellite image.

The study area was analyzed for soil fertility in contrast to the depleted soils of the piedmont. For this purpose, the subsoil depression was isolated (black outline). The thematic maps showed the difference in the composition of fertile (irrigated crops) and infertile soils (smoothing of the relief, loosening of soils in the lowlands).

Further research should be directed at studying the transformation of the soil cover and the manifestation of unfavorable soil degradation processes observed in this area. This is especially true for changes in the conditions of economic activity of agricultural enterprises located within the Petrivskyi depression.

Fig. 10. Thematic maps showing the impact of hostilities on the study area:
a – NDVI, 06/20/2023, Sentinel-2 L2A; b – SWIR1_ Red8_ Blue, 01/01/2024 Sentinel-2 L2A

References

1. Stratehiia zroshennia ta drenazhu v Ukraini na period do 2030 roku [Irrigation and Drainage Strategy in Ukraine for the period until 2030]. Approved by the Cabinet of Ministers of Ukraine on August 14, 2019, No. 688-r. Retrieved from: https://zakon.rada.gov.ua/laws/show/688-2019-p#Text [in Ukrainian].

2. Allred, B.J., Fausey, N.R., Peters, L., Chen, C., Daniels, J.J., & Youn, H. (2004). Detection of buried agricultural drainage pipe with geophysical methods. *Applied Engineering in Agriculture*, 20 (3), 307–318.

3. Schilling, K.E., Jindal, P., Basu, N.B., & Helmers, M.J. (2012). Impact of artificial subsurface drainage on groundwater travel times and baseflow discharge in an agricultural watershed, Iowa (USA). *Hydrological Processes*, 26 (20), 3092–3100.

4. Schilling, K.E., & Helmers, M. (2008). Effects of subsurface drainage tiles on streamflow in Iowa agricultural watersheds: An exploratory hydrograph analysis. *Hydrological Processes*, 22 (23), 4497-4506.

5. Filion, R., Bernier, M., Paniconi C.C., Chokmani, K., Melis, M., Soddu, A., & Talazac, M. (2016). Remote sensing for mapping soil moisture and drainage potential in semi-arid regions: Applications to the Campidano plain of Sardinia, Italy. *The Science of the Total Environment*, Vol. 543, B, 862–876. DOI: https://doi.org/10.1016/j.scitotenv.2015.07.068 .

6. Bergstedt, H, Jones, B.M., Hinkel, K., Farquharson, L., Gaglioti, B., Parsekian, A., Kanevskiy, M., Ohar, N., Grosse, G. (2021). Remote Sensing-Based Statistical Approach for Defining Drained Lake Basins in a Continuous Permafrost Region, North Slope of Alaska. *Remote Sensing*, 13 (13), 2539, 22–26. DOI: https://doi.org/10.3390/rs13132539.

7. Tlapakova, L., Zaloudik, J., Kulhavy, Z., & Pelisek, I. (2015). Use of Remote Sensing for Identification and Description of Subsurface Drainage System Condition. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 63 (5), 1587–1599. DOI: https://doi.org/10.11118/actaun201563051587.

8. Cho, E., Jacobs, J.M., Jia, X., & Kraatz, S. (2019). Identifying subsurface drainage using satellite big data and machine learning via Google Earth Engine. *Water Resources Research*, 55. DOI: https://doi.org/10.1029/2019WR024892

9. Melnychenko, M., & Dyniak, O. (2022). Using Remote Sensing Methods of the Earth to Analyze the Impact of the Bolgrad Drainage System on the Conditions of Groundwater. European Association of Geoscientists & Engineers. *16th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment, Conference paper*, Vol. 2022, 1–5. DOI: https://doi.org/10.3997/2214-4609.2022580179 [in English].

10. Kobryn, H., Lantzke, R., Bell, R., & Admiraal, R. (2015). Remote sensing for assessing the zone of benefit where deep drains improve the productivity of land affected by shallow saline groundwater. Journal of Environmental Management, Vol. 150, 138–148. Bazlar Rashid, Md. (2023). Monitoring of drainage system and waterlogging area in the human-induced Ganges-Brahmaputra tidal delta plain of Bangladesh using MNDWI index. *Heliyon,* Vol. 9 (6), e17412. DOI: https://doi.org/10.1016/j.heliyon.2023.e17412.

11. Northcott, W.J., Ashok, V.K., & Cooke, R.A. (2000). Mapping Subsurface Drainage Systems using Remote Sensing and GIS. Engineering & Materials Science. Technical Papers: Engineering Solutions for a New Century, 2625–2634. ASAE Annual International Meeting, Milwaukee, United States.

12. Savchuk, D.P., Belikov, O.M., & Shevchenko, A.M. (2012). Results of monitoring flooding and sub-flooding of rural areas in conditions of no-flow and drainage [Results of monitoring flooding and sub-flooding of rural areas in conditions of no-flow and drainage]. *Suchasnyi stan ta perspektyvy rozvytku upravlinnia vodnymy resursamy Ukrainy* : materialy nauk.-prakt. konf. red. kol. A. Stashuk: DIEVR, 23–24. [in Ukrainian].

13. Babitska, O.A., Kharlamov, O.I., Kotykovych. I.V., Zemlyanska, D.P., Bozhenko, R.P., Belikov, O.M., & Medvedeva, O.O. (2019). Pidsumky naturnykh doslidzhen inzhenernoho drenazhu [Results of field studies of engineering drainage]. *Melioratsiia i vodne hospodarstvo*, Vol. 2, 87–95. [in Ukrainian].

14. Savchuk, D.P., Kharlamov, O.I., & Kotykovych, I.V. (2018). Efficiency of closed horizontal drainage against the background of irrigation of DM “Frehat” [Efficiency of closed horizontal drainage against the background of irrigation of DM “Fregat”]. Mizhvidom. tematych. nauk. zb.

Melioratsiia i vodne hospodarstvo, Vol. 1 (107), 30–36. DOI: https://doi.org/10.31073/mivg201801-109 [in Ukrainian].

15. Savchuk, D.P., Babitska. O.A. Kharlamov. O.I., Kotykovych, I.V., Zemlyanska, D.P., & Bozhenko, R.P. (2019). Rezultaty polovykh sposterezhen za efektyvnistiu inzhenernoho drenazhu. [Results of field observations on the efficiency of engineering drainage]. Mizhvidom. tematych. nauk. zb. *Melioratsiia zemel ta vodne hospodarstvo*, Vol. 2, 87–95. DOI: https://doi.org/10.31073/mivg201902-205 [in Ukrainian].

16. Topohrafichna karta Ukrainy. Retrieved from: https://uk-ua.topographic-map.com/mapls7gb3/%D0%A3%D0%BA%D1%80%D0%B0%D1%97%D0%BD%D0%B0/?center=46.44352%2C34.65002&zoom=12

17. Institute of Hudraulic Engeneering and Land Reclamation. (2005). Skhema of comprehensive protection of silskohospodar uhid and naselenykh punktiv Kherson region from the flooding of gruntovymy vodam and zatoplennya poverkhnevymy vodam [Scheme of comprehensive protection of agricultural lands and settlements of the Kherson region from groundwater flooding and surface water flooding]. Zahalna poiasniuvalna zapyska. Knyha 1. Kyiv. [in Ukrainian].

18. Vozhegova, R.A. (2021). Dynamika zmin temperaturnogo regymu i kilkosti opadiv v Khersonskiy oblasti v kontexsti zmin klimatu [Dynamics of changes in temperature regime and precipitation in the Kherson region in the context of climate change]. *Agrarni inovazii: melioratsiia, zemlerobstvo, roslynnytstvo*, 5, 17–21 [in Ukrainian].

19. Institute of Water Problems and Land Reclamation. (2020). Pro stan vodnych resursiv dergavy ta osoblyvosti silskogospodarskogo vyrobnyztva v umovakh zmin klimatu. Informazijno – analitychna dovidka [On the state of the state's water resources and the peculiarities of agricultural production in the context of climate change. Information and analytical reference]. Kyiv. Retrieved from: http://naas.gov.ua/upload/iblock/78a/Інформаційна%20довідка%204.05.2020-конвертирован.pdf [in Ukrainian].

УДК 631.4:631.47

ПРОСТОРОВО-ЧАСОВІ ЗМІНИ ЕКОЛОГО-МЕЛІОРАТИВНОГО СТАНУ БЕЗСТІЧНИХ ТЕРИТОРІЙ

О.В. Власова[1], докт. с.-г. наук, Дмитро Савчук[2], канд. техн. наук, І.А. Шевченко[3], канд. техн. наук, А.М. Шевченко[4], канд. с.-г. наук , О.М. Козицький[5]

[1] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0002-1911-4329; e-mail: elena_vl2001@ukr.net;
[2] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0001-7683-6005; e-mail:savchuk_igim@mail.com;
[3]Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0002-7401-8786; e-mail: irashef@ukr.net;
[4] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0002-2637-6538; e-mail: monitoring_protect@ukr.net;
[5] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid. org/0000-0002-4459-6331; e-mail: olegkoz@ukr.net

Анотація. *У статті викладено результати досліджень просторово-часових змін еколого-меліоративного стану безстічних територій, які ґрунтуються на використанні супутникових даних високого та середнього просторового розрізнення. Автори оцінили геоморфологічні, гідрогеологічні та ґрунтово-меліоративними умови степової зони України та зазначили, що неоднорідні природні умови такі як рельєф, геоморфологія, підземні води, ґрунти та породи зони активного водообміну, сприяли розвитку процесів шкідливої дії вод та характеру їх прояву. За об'єкт дослідження обрано велику безстічну територію – Петрівський под в районі Каховської зрошувальної системи. Процеси деградації земель на території поду ідентифіковано шляхом виявлення різноманітних проявів спектрально-текстурних змін ґрунтово-рослинних поверхонь під дією водної та вітрової ерозії, незбалансованої системи землекористування на основі супутникових знімків різних систем сканування земної поверхні. Зміни визначали і вивчалися за вегетаційними, ґрунтовими і водними спектральними індексами, що дозволило спостерігати за підтопленням території. Спостереження велися в різні роки і в цілому охоплюють період у понад 40 років: 1985–2015 рр. – спостерігалися найактивніші підтоплення території; 2002, 2003 і 2005 рр. – масштабні зимово-весняні затоплення;*

2018–2024 рр. – зафіксована відсутність роботи дренажної системи, яка знаходиться у занепаді; 2023, 2024 рр. – вплив ведення бойових дій на територію поду. За результатами досліджень просторової диференціації ґрунтових виділів, а також їх часової динаміки авторами розроблено комплексний показник, який є функцією трьох складових – спектральних індексів NDVI, NDWI та CM. Верифікація досліджень періоду 1991–2017 рр. усереднених значень спектральних індексів показала, що найбільш тісний кореляційний зв'язок існує між NDWI та NDVI і становить 0,92. Дослідну територію було проаналізовано щодо родючості ґрунтів на контрасті зі збідненими ґрунтами поду. Визначено, що із зміною концентрації гумусу змінюється забарвлення верхнього шару ґрунту, що в свою чергу викликає зміни в спектральних характеристиках супутникового знімка. Шляхом багаторічних спостережень вивчено просторово-часові зміни еколого-меліоративного стану безстічної території та ймовірність втрати функціонального ресурсу меліоративної системи в цілому.

Ключові слова: *безстічні території, осушувальна система, еколого-меліоративний стан, супутникові дані, спектральні індекси, просторово-часові зміни*

DOI: https://doi.org/10.31073/mivg202501-415
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/415

UDC 556.132.2

THE IMPACT OF CLIMATE CHANGE ON EVAPORATION FROM THE RESERVOIRS OF THE SOUTHERN BUG BASIN

O.M. Kozytskyi[1], A.M. Shevchenko[2], Ph.D in Agricultural Sciences, O.V. Vlasova[3], Dr. of Agricultural Sciences, Y.V. Shevchuk[4], I.A. Shevchenko[5], Ph.D. in Technical Sciences
[1] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-4459-6331; e-mail: olegkoz@ukr.net;
[2] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-2637-6538 ; e-mail: monitoring_protect@ukr.net;
[3] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-1911-4329; e-mail: elena_vl2001@ukr.net;
[4] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-6718-3874; e-mail: yaroslav_shevchuk@ ukr.net;
[5] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-7401-8786; e-mail: irashef@ukr.net

Abstract. *The article deals with the issue of assessing the level of flow regulation of the Southern Bug River Basin within Khmelnytskyi and Vinnytskyi regions. The Southern Bug River Basin is one of the most regulated river basins in Ukraine, with 17 % of reservoirs and 20 % of ponds of the total number in Ukraine. Many of them are in extremely poor condition. Overgrowth, siltation, and bank degradation in many small reservoirs have led to a significant reduction in their volume, an increase in the area of shallow water, disrupted soil nutrition, and caused intensive development of higher aquatic vegetation. Studies have shown that water losses to evaporation in the reservoirs of this basin amount to 25,6 % of their total volume, or 50,2 % of the useful volume. At the ponds, losses are much higher and amount to 66,7 % of their total volume. In general, evaporation losses in the Southern Bug River (up to the border with Kirovohradskyi region) amount to 17,6 % of its average annual value over the long-term observation period. A significant increase in evaporation from the water surface has been observed in recent decades, due to an increase in air temperature during the growing season. While in the very low-water years of the last century, evaporation losses of the Southern Bug amounted to 38,3 % of the annual runoff, in 2020 they reached almost 70 %. The greatest increase in evaporation is observed in the summer months, due to an increase in daily maximum air temperatures and the number of days with average daily air temperatures above 30 °C. To solve the problem of conservation and efficient use of water resources, it is necessary to introduce a comprehensive system of organizational and technical measures, including optimization of the number of reservoirs in river basins, taking into account the level of flow regulation and economic needs; increasing the volume of functioning reservoirs by clearing their l*

Keywords: *anthropogenic load, evaporation, reservoir, flow regulation, precipitation, river basin, ponds*

Relevance of the research. Ukraine belongs to the countries with insufficient water resources, which necessitates intensive regulation of surface runoff. According to the UN economic criterion for sufficient water supply, there should be at least 1700 m^3 of water per person per year, and in Ukraine, per capita water supply is about 1200 m^3[1]. In the southern and eastern regions of Ukraine, reservoirs are practically the only source of guaranteed supply of drinking water for the population, as well as for the needs of municipal, agricultural, and industrial sectors for fresh water. Ukraine ranks second in Europe in terms of the number of reservoirs, after Spain. In total, there are 1054 reservoirs and 49444 ponds in the country, with a total area of 2891 km^2 [2, 3]. Reservoirs are used depending on the economic specialization of the region, in particular for runoff regulation and flood control, water supply, irrigation, fish farming, hydropower, and recreation. Flow regulation in the basins of small rivers can reach 70 %, and in the south – all 100 %, which causes significant irreversible losses of water resources and environmental problems caused by deterioration of water quality, channel deformations, intensification of eutrophication processes, flooding, etc.

Ukraine's reservoirs play an important role in providing water resources, but a significant part of them is in a very poor condition. Overgrowth, siltation, and bank degradation in many small water bodies have led to a significant reduction in their volume, an increase in the area of shallow water, disrupted soil nutrition, and caused intensive development of higher aquatic vegetation in warmed and fertile shallow areas. The increase in nutrient inputs, which are the source of nutrition for bacteria and aquatic vegetation, led to the “blooming” of water as a result of the development of blue-green algae.

Chemical, bacteriological, and biological pollution is a common occurrence in reservoirs and ponds, especially those built on small rivers and without a balance holder. Pollution of water bodies makes it impossible to use them as sources of water resources. The technical condition of hydraulic structures on these reservoirs is also unsatisfactory, which often makes it impossible to ensure the necessary flow regulation and environmental releases and discharges into the lower reaches. Many of the reservoirs have lost their economic significance and are only water intakes for local surface runoff and additional evaporators of water. Therefore, the problem of rational use of water resources in Ukraine is extremely relevant.

Analysis of recent studies and publications. Extensive scientific research on the problem of conservation and rational use of water resources and assessment of the environmental impact of reservoirs has been conducted in Ukraine since the construction of the Dnipro reservoirs cascade. Papers [2–5] provide data on the quantitative assessment of water bodies in Ukraine within the main river basins and administrative units, as well as their main hydromorphological and technical characteristics. Based on long-term studies, the State Agency of Ukraine for Water Resources has developed the Rules for the Operation of Reservoirs of the Dnipro and Dniester Cascades to ensure effective flow regulation. For other water bodies, the territorial bodies of the State Agency of Ukraine for Water Resources have determined the procedure for establishing their operating regimes [6].

A large number of studies have been devoted to assessing the negative impact of artificial reservoirs on the ecological state of the natural environment, including flooding of territories, changes in the hydrological regime of rivers, activation of channel processes, changes in biodiversity and fish fauna, etc. [7–9]. A considerable amount of research is devoted to the deterioration of water quality, hydrochemical and hydrobiological regimes, eutrophication of water bodies, especially algal blooms [10, 11], as well as water balance studies, in particular, on runoff losses due to evaporation [12–15]. These studies point to the need to implement a comprehensive system of measures to improve the ecological status of water bodies and conserve and rationally use water resources, including improving flow control schemes by quantitatively optimizing ponds and reservoirs and reducing evaporation and filtration losses.

The aim of the study is to assess the level of runoff regulation of Ukrainian rivers and to substantiate promising measures to preserve water availability.

Research methods. The research was carried out on the basis of generally accepted methods of synthesis and analysis of long-term hydrometeorological observation data published in the materials of the State Water Cadastre and the Climate Cadastre of Ukraine, as well as literature on this issue.

Research results and their discussion. The Southern Bug River basin is one of the most heavily regulated river basins in Ukraine. It is home to 17 % of reservoirs and 20 % of ponds out of the total number of reservoirs in Ukraine. Table 1 shows the average annual evaporation from the surface of water bodies and its value as a percentage of the water volume in ponds and reservoirs for the Southern Bug section up to the border of Vinnytsia and Kirovohrad oblasts. In the calculations, the evaporation value of 650 mm was assumed, according to the corresponding map of the Climate Atlas of Ukraine. The analysis of the table shows that evaporation losses at the reservoirs amount to 25,6 % of their total volume, or 50,2 % of the useful volume. At ponds, losses are much higher and amount to 66,7 % of their total volume. This is due to the much shallower depths of small reservoirs and, accordingly, much larger water mirror areas per unit volume.

It should be noted that water losses due to evaporation from ponds and reservoirs within the Khmelnytsky section of the basin are higher than within the Vinnytsia region, due to the shallower depths of water bodies in Khmelnytsky. In total, evaporation losses within this section of the Southern Bug basin amount to 258,25 million m^3 on average per year, or 42,8 % of their total volume. In general, the total evaporation losses from the basin’s water bodies (ponds and reservoirs) are 44 % higher than the useful volume of all reservoirs.

The average annual discharge of the Southern Bug River according to observations at the Pidhiria hydrological station located on the border of Kirovohradskyi and Mykolaivskyi regions is 56,2 m^3/s. In terms of the border of Vinnytskyi and Kirovohradskyi regionss, it is 46,6 m^3/s, and the average annual volume of the river flow is 1469,58 million m^3.

1. Regulating the flow of the Southern Bug River up to the border with Kirovohradskyi region

Region	**Number of reservoirs**	**Area of the river ha**	**Volume, million m^3**		**Evaporation**	**Evaporation losses**	
						of total volume	**of useful volume**
			full	**useful**	**Million m^3**	**%**	**%**
Reservoirs							
Vinnytska	42	8604	269,0	117,0	55,93	20,8	47,8
Khmelnytska	24	5241	82,5	62,2	34,07	41,3	54,8
Total	66	13845	351,5	179,2	90,00	25,6	50,2
Rates in							
Vinnytska	3401	17614	182,0		114,49	62,9	
Khmelnytska	976	8271	70,4		53,76	76,4	
Total	4377	25885	252,4		168,25	66,7	
Total for the Southern Bug basin (up to the border of Kirovograd region)							
		39730	603,9		258,25	42,8	144,1

Since the average annual volume of evaporation from the reservoirs of the Southern Bug basin within Khmelnytskyi and Vinnytskyi regions is 258,25 million m^3 the loss of river flow due to evaporation is 17,57 %. The lowest average annual river discharge at the Pidhiria settlement in the last century was 25,7 m^3/s (1995), which corresponds to a discharge of 21,31 m^3/s at the region's border, or a runoff of 673,9 million m^3. Accordingly, evaporation from the reservoirs of the Southern Bug in the Khmelnytski and Vinnytskyi regions in the very low-water years of the last century reached 38,32 % of the annual river flow.

As noted above, the evaporation (Table 1) is calculated based on the average evaporation data shown on the zoned map of the Climate Atlas of Ukraine, which was built on the basis of the Climate Cadastre of Ukraine for 1961–1990 and, accordingly, does not take into account the climate changes observed in Ukraine in recent decades. Figure 1 shows the dynamics of the Southern Bug River flow based on observations at the Pidhiria hydrological post since 1927, which shows a sharp decrease in river flow since 2007. In 2020, the river flow was more than twice as low as the lowest flow recorded during the above observation period and amounted to 371,32 million m^3. Accordingly, evaporation from the reservoirs of the Southern Bug in the Khmelnytskyi and Vinnytskyi regions reached almost 70 % of the river's annual runoff.

An analysis of the intra-annual distribution of runoff (Fig. 2) for the periods before 2000 and 2000–2020 shows that the largest decrease in runoff was recorded during the spring flood and from July to September. In the first case, this is due not only to climate change, in particular a decrease in snow reserves in the basin, but also to flow regulation, since the volume of spring filling of reservoirs before the normal headwater level of reservoir depends on the level of their operation at the beginning of the flood. Due to climate change in recent decades, the level of pre-flood filling of reservoirs has decreased significantly. The decrease in runoff during the warm season is due to the maximum increase in daily maximum air temperatures, which have repeatedly reached historical highs in recent years.

The annual runoff volume is mainly determined by the difference between the amount of precipitation in the basin and evaporation, as well as the irrevocable volume of water withdrawals for economic use. An analysis of precipitation dynamics over a multi-year period (Fig. 3) shows a slight decrease in recent years, which cannot significantly affect a significant reduction in runoff. Accordingly, the sharp decline in river runoff was mainly due to an increase in evaporation, as the number of artificial reservoirs built in recent decades and, accordingly, additional flow regulation is insignificant.

The main reason for the increase in evaporation is air temperature. For example, the average annual air temperature in Kyiv has increased by almost 3 °C in recent decades [5]. Due to the high level of urbanization of the territory (heating networks, a large percentage of paved surfaces, and the level of gas and smoke emissions), this is much higher than in natural areas, where the temperature increase within Ukraine reaches 1–2 °C. In Vinnytsia, the average annual air temperature (modern climatic norm) increased by 1,2 °C between 1991 and 2020 compared to the period 1961–1990 (previous climatic norm) (Table 2). The highest temperature increase was observed in January and February, when evaporation is practically absent, and in the summer months, when evaporation is highest (Fig. 4).

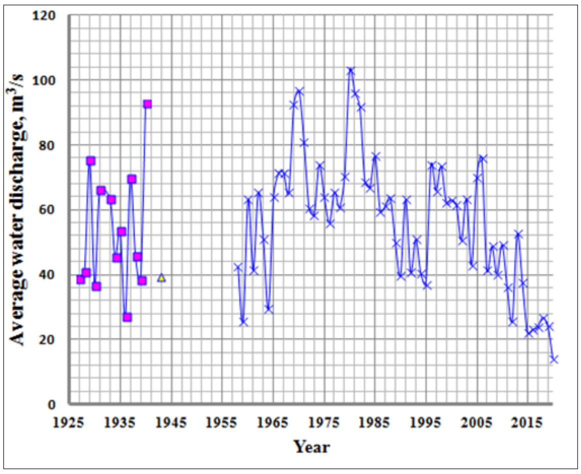


Fig. 1. Dynamics of the average annual runoff of the Southern Bug River – Pidhiria settlement

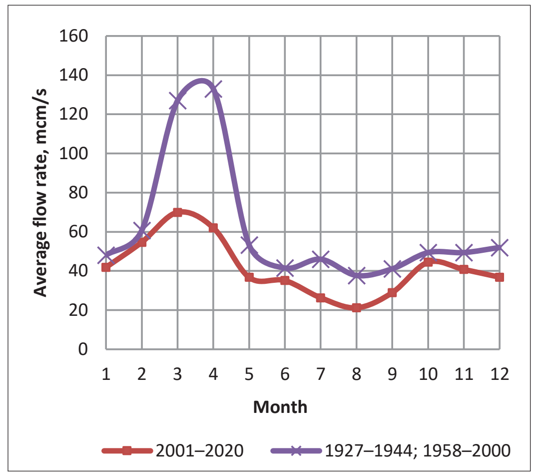


Fig. 2. Distribution of the average annual runoff of the Pivdennyi Buh River – Pidhiria settlement by months for different time intervals

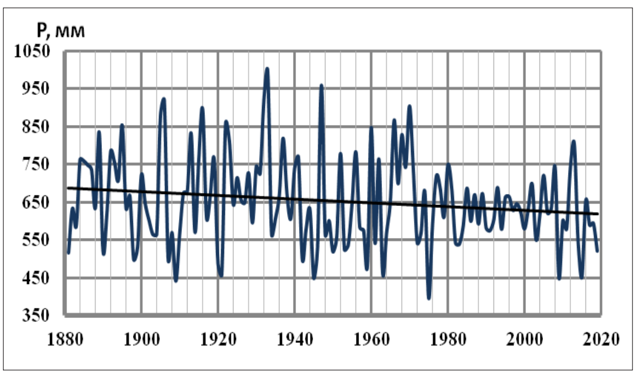


Fig. 3. Dynamics of precipitation in Kyiv over the entire observation period

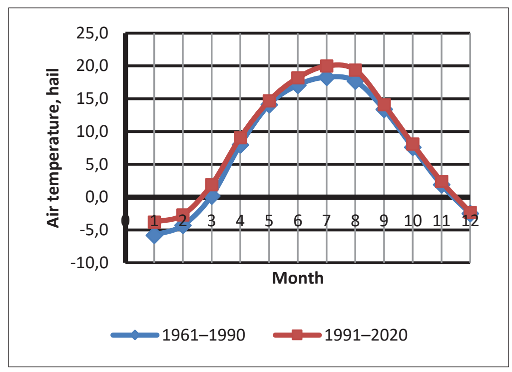


Fig. 4. Intra-annual distribution of air temperature, Vinnytsia city

2. Air temperature at the Vinnytsia weather station

Period	Month												
Years	1	2	3	4	5	6	7	8	9	10	11	12	Year
1961–1990	–5,8	–4,3	0,2	8,0	14,1	17,1	18,3	17,7	13,4	7,6	1,9	–2,5	7,1
1991–2020	–3,8	–2,7	1,9	9,1	14,7	18,2	20	19,4	14,1	8,1	2,4	–2,3	8,3

Fig. 5 shows the dynamics of evaporation from Kyiv reservoirs. To calculate evaporation, an approximate empirical method by A.M. Postnikov was used, based only on the dependence of evaporation on the sum of monthly air temperatures during the frost-free period. The formula was derived from instrumental measurements of evaporation and air temperature on the largest reservoirs of the former USSR. The calculations show a sharp increase in evaporation since 1997.

Fig. 6a shows a graph of the dependence of daily evaporation from the water surface on air temperature, which is based on field data measured in DGI-300 evaporators [15]. The analysis of the graph shows that evaporation increases proportionally with increasing air temperature only up to a temperature of 16 °C, when the increase in evaporation for each degree of temperature increase ranges from 0 to 0,3 °C (Fig. 6b) With further increase in temperature (T), the increase in evaporation (P) increases according to a polygonal dependence (Fig. 7), approximated by Eq:

$$P = 0.0115T^2 - 0.0559T + 0.5333 \quad (1)$$

In the temperature range from 17 to 40 °C, the evaporation increase varies from 0,3 to 0,9 mm for each degree of increase in daily temperature (Table 3).

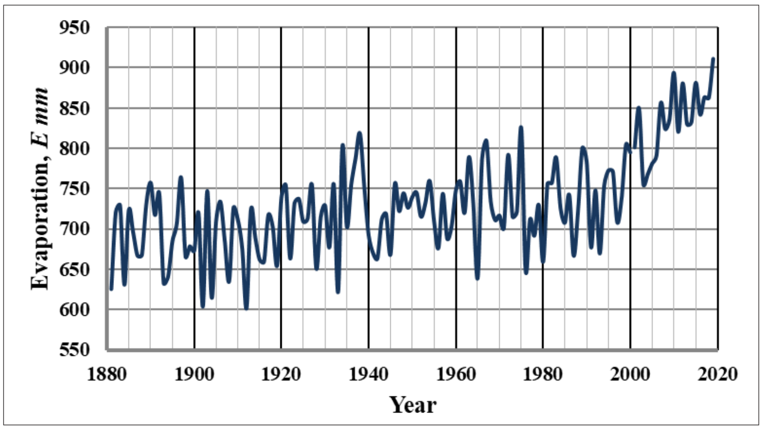
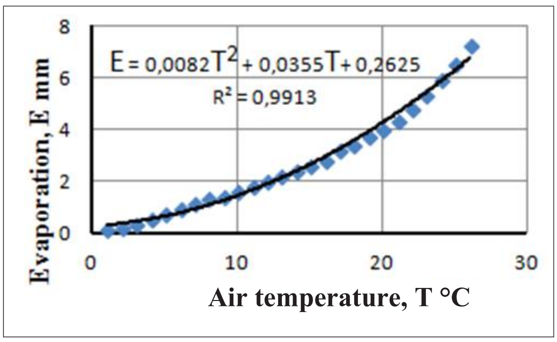
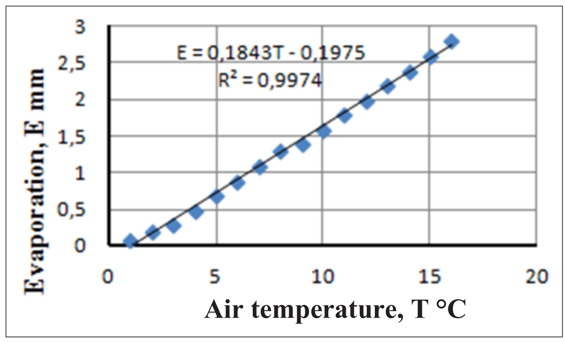


Fig. 5. Estimated evaporation from the water surface of Kyiv reservoirs since 1881



a)



b)

Fig. 6. Dependence of evaporation on air temperature:
a) polygonal dependence; b) linear dependence in the low temperature range.

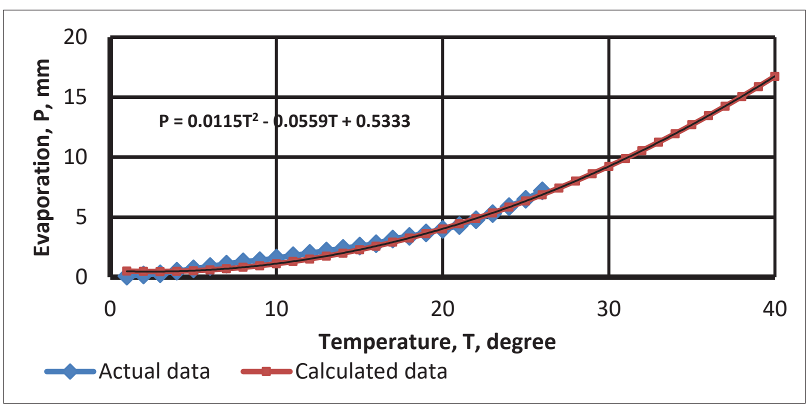


Fig. 7. Dependence of evaporation on air temperature

These results show that the evaporation rate is not proportional to the increase in air temperature, but increases sharply at its maximum values, especially when the temperature exceeds 30 °C. The last two decades have been characterized not only by an increase in the average annual temperature, but also by a sharp increase in average daily temperatures in the summer months. In these years, most of the historical temperature maximums were exceeded. Thus, while in Kyiv from 1971 to 2006 there were an average of 9 days with temperatures above 30 °C, from 2007 to 2020 the number of such days per year increased to an average of 24 (Fig. 9). In 2010, there were 44 days with temperatures above 30 °C [15].

3. Dependence of daily evaporation from the water surface on air temperature in Ukraine

Temperature, °C	Evaporation, P, mm	Evaporation increase by 1 °C, (ΔP/1 °C)	Temperature, °C	Evaporation, P, mm	Evaporation increase by 1 °C, (ΔP/1 °C)	Temperature, °C	Evaporation, P, mm	Increase in evaporation by 1 (0) C, (ΔP/1 °C)
1	0,5	0,0	15	2,3	0,3	28	8,0	0,6
2	0,5	0,0	16	2,6	0,3	29	8,6	0,6
3	0,5	0,0	17	2,9	0,3	30	9,2	0,6
4	0,5	0,0	18	3,3	0,3	31	9,9	0,6
5	0,5	0,0	19	3,6	0,4	32	10,6	0,7
6	0,6	0,1	20	4,0	0,4	33	11,2	0,7
7	0,7	0,1	21	4,4	0,4	34	12,0	0,7
8	0,8	0,1	22	4,9	0,4	35	12,7	0,7
9	1,0	0,1	23	5,3	0,5	36	13,5	0,8
10	1,1	0,2	24	5,8	0,5	37	14,2	0,8
11	1,3	0,2	25	6,3	0,5	38	15,1	0,8
12	1,5	0,2	26	6,9	0,5	39	15,9	0,8
13	1,7	0,2	27	7,4	0,6	40	16,7	0,9
14	2,0	0,3						

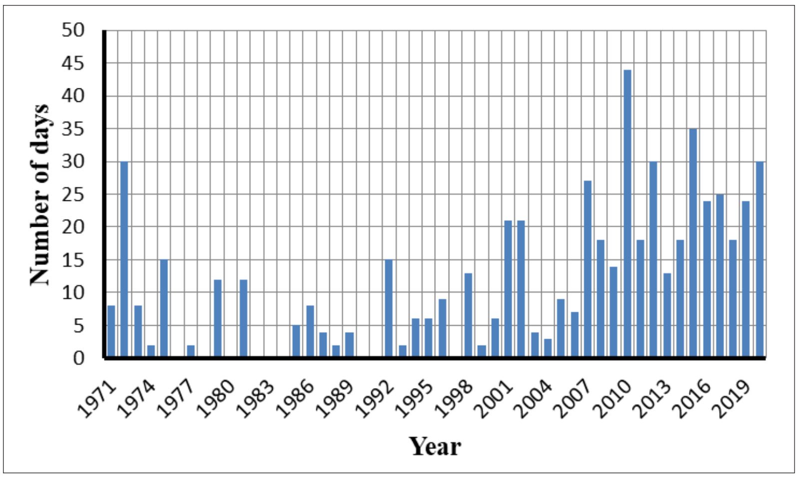


Fig. 8. Number of days with average daily temperature above 30° C, Kyiv

The calculations based on the formula for the dependence of daily evaporation on temperature showed that in the period from 1991 to 2020, the average annual evaporation increased by 81 mm compared to the period 1961–1991, and in July and August, monthly evaporation increased by 20 mm.

Conclusions. The increase in the intensity of evaporation from the water surface in recent decades has caused a significant decrease in water resources in Ukraine, which is primarily due to excessive losses of runoff due to evaporation from the surface of ponds and reservoirs, a significant part of which is in poor environmental condition and has a low level of use efficiency. Water losses by evaporation from the reservoirs of the Southern Bug basin within Khmelnytsky and Vinnytsia oblasts can reach 70 % of the total annual runoff in very dry years. To solve the problem of conservation and efficient use of water resources, it is necessary to implement a comprehensive system of organizational and technical measures, including: optimization of the number of reservoirs in river basins, taking into account the level of flow regulation and economic needs; increasing the volume of functioning reservoirs by clearing their beds (taking into account hydrogeological conditions); elimination of shallow reservoirs or reduction of the area of their shallow areas; restoration of water sources; clearing of water sources in their upper reaches.

References

1. Yatsyuk, M.V. (2024). Development of scientific principles of water safety: dissertation. IWPaLM NAAS, Kyiv.

2. Hrebin, V.V., Khilchevsky, V.K., Stashuk, V.A., Chunaryov, O.V., & Yaroshevich, O.E. (2014) Vodnyi fond Ukrainy. Shtuchni vodoimy. Water Fund of Ukraine. Artificial reservoirs. Reservoirs and ponds]. Kyiv: Interpres, 163. [in Ukrainian].

3. Khilchevsky, V.K., & Hrebin, V.V. (2021). Velyki i mali vodoskhovyshcha Ukrainy: rehionalni ta basinovi osoblyvosti poshyrennia [Large and small reservoirs of Ukraine: regional and basin-specific distribution features]. *Hydrolohiia, hidrokhimiia i hidroekolohiia*, 2 (60) [in Ukrainian].

4. Palamarchuk, M.M., & Zakorchevna, N.B. (2001). Vodnyi fond Ukrainy [Water Fund of Ukraine: possible solutions]. Kyiv: Nika-Tsentr, 392 [in Ukrainian].

5. Kozytskyi, O.M., Shevchuk, S.A., Shevchenko, I.A., & Logunova, N.V. (2020). Prychyny ponyzhennia rivnia ozera Synie ta zakhody shchodo pokrashchennia yoho ekolohichnoho stanu [Factors of lowering the Lake Syne levels and measures to improve its ecological state]. *Melioratsiia i vodne hospodarstvo*, 2, 112–188 [Factors of lowering Lake Syne levels and measures to improve its ecological state] [in Ukrainian].

6. Poriadok vstanovlennia rezhymiv roboty shtuchnykh vodnykh obiektiv ta vodohospodarskykh system. Order of the Ministry of Environmental Protection and Water Resources of Ukraine of January 20, 2022 [Procedure for establishing operating modes of artificial water bodies and water management systems. Order of the Ministry of Environmental Protection and Natural Resources of Ukraine dated January 20, 2022]. Retrieved from: https://zakon.rada.gov.ua/laws/show/z0280-22#Text [in Ukrainian].

7. Timchenko, V.M. (2006). Ecological hydrology of reservoirs of Ukraine. [Ecological hydrology of reservoirs of Ukraine]. Kyiv: Nauk. dumka, 383. [in Ukrainian].

8. Dubnyak, S.S. (2007). Ekoloho-hidromorfolohichnyi analiz problem pidtoplennia zemel u zoni vplyvu Dniprovskykh vodoskhovyshch [Ecological and hydromorphological analysis of land flooding problems in the area of influence of the Dnipro reservoirs]. *Nauk. pratsi UkrNDHMI*, 2, 1–15 [in Ukrainian].

9. Shevchuk, V.Ia. (1999). Rekomendatsii shchodo polipshennia ekolohichnoho stanu pryberezhnykh terytorii Dniprovskykh vodoskhovyshch [Recommendations for improving the ecological condition of the coastal areas of the Dnipro reservoirs]. Kyiv: KSP, 182. [in Ukrainian].

10. Pichura, V.I. (2016). Prostorovo – chasovi zminy trofichnoho stanu vodoskhovyshch richky Dnipro [Spatial-temporal changes in the trophic state of the Dnipro River reservoirs]. *Visnyk NUVHP*, 4 (76), 3–21 [in Ukrainian].

11. Tavrel, M.I. (2021). Obhruntuvannia shliakhiv podolannia evtrofikatsii vodoim. [Justification of ways to overcome eutrophication of water bodies]. *Problemy ekolohii*, 1 (23), 73–79 [in Ukrainian].

12. Vishnevsky, V.I., & Kutsy, A.V. (2022). Bahatorichni zminy vodnoho rezhymu richok Ukrainy [Long-term changes in the water regime of Ukrainian rivers]. Kyiv: Naukova dumka, 250 [in Ukrainian].

13. Shereshevsky, A.I., & Synytska, L.K. (2003). Rozrakhunkove vyparovuvannia z vodnoi poverkhni na terytorii Ukrainy Nauk [Estimated evaporation from the water surface on the territory of Ukraine]. *Reports of UkrNDHMI*. 252, 11–19 [in Ukrainian].

14. Shereshevsky, A.I., & Synytska, L.K. (2006). Suchasna otsinka rozrakhunkovoho vyparovuvannia z vodnoi poverkhni dniprovskykh vodoskhovyshch z metoiu yogo vrakhuvannia pry rozrobtsi rezhymiv roboty HES [Modern assessment of calculated evaporation from the water surface of the Dnieper reservoirs in order to take it into account when developing the operating mode of the hydroelectric power station]. *Nauk. pratsi UkrNDHMI*, 255, 213–227. [in Ukrainian].

15. Obukhov, E.V. (2014). Determination of water losses due to evaporation from Dneprovsky reservoirs using a generalized formula [Determination of water losses due to evaporation from Dneprovsky reservoirs using a generalized formula]. *Ukrainian Hydrometeorological Journal*, 14, 136–143 [in Ukrainian].

16. Vyshnevskyi, V.I., Donich, O.A., & Kutsy, A.V. (2023). Climate of Kyiv and its surroundings [Climate of Kyiv and its surroundings]. Kyiv: Varto, 124. [in Ukrainian].

УДК 556.132.2

ВПЛИВ КЛІМАТИЧНИХ ЗМІН НА ВИПАРУВАННЯ З ВОДОЙМ БАСЕЙНУ ПІВДЕННОГО БУГУ

О.М. Козицький[1], А.М. Шевченко[2], канд. с.-г. наук, О.В. Власова[3], докт. с.-г. наук, Я.В. Шевчук[4], І.А. Шевченко[5], канд. техн. наук

[1] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid. org/0000-0002-4459-6331; e-mail: olegkoz@ukr.net;
[2] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0002-2637-6538; e-mail: monitoring_protect@ukr.net;
[3] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0002-1911-4329; e-mail: elena_vl2001@ukr.net;
[4] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0001-6718-3874; e-mail: yaroslav_shevchuk@ ukr.net;
[5] Інститут водних проблем і меліорації НААН, Київ, 03022, Україна;
https://orcid.org/0000-0002-7401-8786; e-mail: irashef@ukr.net

Анотація. *Висвітлено питання щодо оцінки рівня зарегулювання стоку річок басейну Південного Бугу в межах Хмельницької та Вінницької областей. Басейн Південного Бугу є одним з найбільш зарегульованих річкових басейнів України, де знаходиться 17 % водосховищ і 20 % ставків від їх загальної кількості в Україні. Значна їх частина знаходиться у вкрай незадовільному стані. Заростання, замулення, деградація берегів на багатьох малих водоймах призвели до значного зменшення їхнього об'єму, збільшення площі мілководь, порушили умови грунтового живлення та спричинили інтенсивний розвиток вищої водної рослинності. Виконані дослідження показали, що на водосховищах зазначеного басейну втрати води на випарування становлять 25,6 % від їх повного сумарного об'єму, або 50,2 % від корисного. На ставках втрати значно вищі і становлять 66,7 % їхнього сумарного об'єму. У цілому втрати стоку Південного Бугу на випарування (до межі з Кіровоградською областю) становлять 17,6 % від його середньорічного значення за багаторічний період спостережень. Значне зростання випарування з водної поверхні спостерігається в останні десятиліття, що обумовлено підвищенням температури повітря у вегетаційний період. Якщо у дуже маловодні роки минулого століття втрати на випарування Південного Бугу становили 38,3 % річного стоку, то у 2020 році вони сягнули майже 70 %. Найбільше зростання випарування спостерігається в літні місяці, що зумовлено зростанням добових максимумів температур повітря та кількості днів з середньодобовими температурами повітря понад 30 °С. Для вирішення проблеми збереження й ефективного використання водних ресурсів необхідне впровадження комплексної системи організаційних і технічних заходів, що включають оптимізацію чисельності водойм у басейнах річок з врахуванням рівня зарегулювання стоку та господарських потреб; збільшення об'єму функціонуючих водойм за рахунок розчищення їх ложа; ліквідацію мілких водойм, або зменшення площі їх мілководних ділянок; відновлення природних джерел живлення водойм; забезпечення нормальних умов роботи регулювальних споруд у відповідності з правилами їх експлуатації, а також впровадження системи заходів щодо покращення екологічного стану водойм.*
Ключові слова: *антропогенне навантаження, випарування, водосховище, зарегулювання стоку, опади, річковий басейн, ставки*

DOI: https://doi.org/10.31073/mivg202501-416
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/416

UDC: 556.5:551.58

ESTIMATION OF WATER LOSS FOR TOTAL EVAPORATION FROM THE SURFACE OF PONDS AND RESERVOIRS IN THE INGULETS RIVER BASIN

V.P. Kovalchuk[1], Dr. of Technical Sciences, O.M. Nechai[2], Ph.D., H.A. Balykhina[3], Ph.D., O.P. Voitovych[4], Ph.D.

[1] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0001-7570-1264, e-mail: volokovalchuk@gmail.com;
[2] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0003-0365-1864; e-mail: water_2019@ukr.net;
[3] National Academy of Agrarian Sciences of Ukraine, Kyiv, Ukraine;
https://orcid.org/0000-0002-5571-3556, e-mail: maslova-anna@ukr.net;
[4] Institute of Water Problems and Land Reclamation of NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-1513-4744; e-mail: aleksvoitovych@gmail.com

Abstract. *The article considers the problem of water loss due to the evaporation from the surface of ponds and reservoirs under conditions of intense anthropogenic load and climate changes, focusing on the Ingulets river basin as an example of the one of the most regulated river systems in the steppe zone of Ukraine. Taking into account the growing shortage of water resources, especially after the explosion of the Kakhovka HPP, the relevance of studying evaporation from water surfaces of artificial reservoirs in the southern regions is increasing. Estimating water losses due to the evaporation from the surface of ponds and reservoirs in the Ingulets River basin is an important aspect of water resources management in the region. Available data on the areas of artificial water bodies and average evaporation rates were used to calculate total water losses. Based on a spatial analysis of over 1,200 water bodies in the Inhulets river basin, including an assessment of the areas and volumes of reservoirs and ponds, a quantitative assessment of water evaporation from their surface was carried out for 1961–1990 and 1991–2023. The research methodology is based on the processing of long term meteorological data from local weather stations, as well as the use of satellite and archival information from available sites. Climatic conditions in the studied region demonstrate a steady warming trend: over the past 30 years, the average annual temperature in the Ingulets river basin has increased by an average of 1,3 °C with slight decreases in precipitation over the studied period. It has been found that under modern conditions, evaporation can exceed the inflow from atmospheric precipitation, which turns artificial reservoirs into active factors in reducing the water balance of the Ingulets river basin. In 1991–2023, evaporation rates from the surface of water bodies increased by 13,7 % (107 mm) for the Znamyanka weather station, by 7,6 % (68 mm) for the Komisarivka weather station, and by 9,1 % (88 mm) for the Kryvyi Rih weather station. Particular attention is paid to assessing the water management efficiency of the functioning of such facilities in the context of environmental safety, hydrological stability, and adaptation to the climate changes. The obtained results are important for the development of regional water resources management strategies, improvement of methods for calculating water losses, and ecological and economic optimization of the water fund structure in small and medium-sized river basins.*

Key words: *Inhulets river basin, evaporation, climate change, artificial objects, ponds and reservoirs, water balance, water resources management*

Relevance of the research. Excessive regulation of river flow is one of the main water problems of Ukraine [p. 3, 1], which causes additional water losses due to evaporation, slowing down of water exchange and, as a result, the deterioration of water quality and degradation of riverbeds [p. 4, 1]. This is especially true for the Ingulets river basin, 80 % of the flow of which is regulated by artificial reservoirs [p. 69, 2].

On the one hand, the reservoirs and ponds of the Inhulets river contribute to the accumulation of Dnipro waters [2], which flow through the Dnipro-Inhulets Canal, providing an important water management function of technical and drinking water supply, irrigation, development of aquaculture, etc. On the other hand, these artificial reservoirs reduce river flow due to increased evaporation [2].

Therefore, evaporation is not a clear-cut problem, but becomes critical in cases where the volume of water losses approaches the volume of natural inflow, especially in regions with insufficient moisture availability. In the context of planning and operating water management systems, it is important to consider not only the volumes of useful water consumption, but also losses associated with evaporation [3].

Thus, a detailed study of the spatiotemporal patterns of evaporation in the Ingulets river basin, its relationship with climatic parameters and water use is relevant from both a scientific and an practical point of view.

Analysis of recent research and publications. Evaporation from water surface is a complex physical process, which depends on the surface temperature of air and water, wind direction and speed, depths of water bodies, aquatic vegetation, etc [4–9]. However, an estimate of evaporation losses with sufficient accuracy for practice can be obtained using data from relatively small evaporators and evaporation basins [10], using series of meteorological observations [11], including analogues [12].

Rudakov G.V., Gapich G.V. and Chushkina I.V. [13] determined the water loss due to evaporation from the water surface of the regulating basin on Petrykivka irrigation system (Tsarychanske MUVG) and proved that in August 2016, water losses due to evaporation from water surface exceeded water inflow with precipitation for the previous two months by more than 2,5 times. At that time, evaporation losses increased from 389,2 m^3 (RB-6) to 803,6 m^3 (RB-3), which was mostly caused by meteorological conditions. V.M. Korbutyak and D.V. Stefanyshyn [12] established that for a low-water year of 75 % water availability for the summer period (duration 92 days), a total of 391 mm, or 4,25 mm/day, evaporates from the water surface of the Basivkut reservoir (Rivne city). According to the V.G. Andreev, G.V. Gapich [14], the vast majority of small rivers in the steppe zone of Ukraine today do not meet the criteria of a natural water body, they are cascades of artificial evaporation ponds, have no hydraulic connection with each other, and lose water uselessly and irreversibly [p. 31, 15].

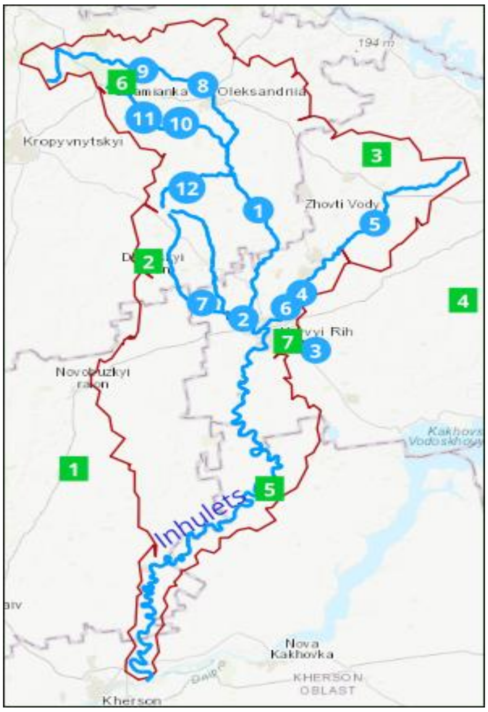
In [16] it is stated that the annual average volume of the Ingulets runflow at the Kryvyi Rih measurement point before the Saksagan river flows into it is approximately 240 million m^3. To a large extent, this is water from the Dnipro river, supplied by the Dnipro-Inhulets canal from the Kremenchuk reservoir. In [16] it is indicated that approximately half of the river's flow is spent on irrigation, evaporation, and filtration. The minimum ecological flow for the Ingulets river is recommended by the flushing regulations and is up to 5,0 m^3/s [17]. Within the Inhulets river basin, two regions are distinguished by their geological structure: the northern part is within the Ukrainian Crystalline Shield, the southern part is in the Black Sea Depression [2]. As a result, groundwater flow in the Inhulets river basin is insignificant.

Andreev V.G. and Gapich G.V. state that for the stabilization and restoration of the hydrological and ecological state of small and medium-sized rivers of the steppe zone of Ukraine, the following are relevant [14]: assessment of the compliance of the existing number of ponds and small reservoirs in river basins with the requirements of the Water Code of Ukraine; ecological and economic justification of the feasibility of further operation for each individual reservoir and facility; development of regional programs for the elimination of ponds and reservoirs that do not perform their water management functions and create an ecological hazard to the functioning of the river ecosystem of the basin; further improvement of methodological approaches to assessing the level of ecological safety of water management facilities in small river basins.

The explosion of the Kakhovka hydroelectric power station dam on June 6, 2023 led to a large-scale environmental and humanitarian disaster in southern Ukraine [18]. There was a need to provide water to the affected regions [19]. In response, a large-scale project was implemented. "Ingulets-Pivdenne reservoir" waterway was built. It ensured the supply of 400 thousand cubic meters of water per day to the Southern reservoir, from where water is supplied to consumers through a purification system [20]. This became an additional load on the existing Inhulets river basin, since before the Kakhovka dam was blown up, water was supplied to the Pivdenne reservoir via the Dnipro-Kryvyi Rih canal from the Kakhovka reservoir.

The aim of the study is to assess water losses due to evaporation from the surface of ponds and reservoirs in the Ingulets river basin in the context of modern climate changes and intensive anthropogenic load. This study will contribute to increasing the accuracy of water management planning, in particular regarding the assessment of water supply, flow regulation, and optimization of the operation of artificial reservoirs in changing climatic conditions.

The object of research. The Ingulets river belongs to the middle size rivers and is a right tributary of the Dnipro, flowing through the Kirovohrad, Dnipropetrovsk, Mykolaiv and Kherson regions of Ukraine, with a length of approximately 549 km and a basin area of 14,870 km² (Fig. 1) [2].



▪ – weather stations:
1. Bashtanska,
2. Dolynska,
3. Komisarivka,
4. Loskharivka,
5. Velyka Oleksandrivka,
6. Znamenka,
7. Kryvyi Rih

● – reservoirs:
1. Iskrivske,
2. Karachunivske,
3. Pivdenne,
4. Kresovske,
5. Makartivske,
6. Saksaganske,
7. Khrystoforivske,
8. Oleksandriyske (Voynivske),
9. Dykivske,
10. Ivanivske,
11. Svitlopilske,
12. Verblyuzheske (Pogrebynske)

Fig. 1. Research object, Ingulets river basin

The Ingulets river basin contains a significant number of reservoirs and ponds and they play an important role in water supply, irrigation, and recreation. There are more than 1200 water bodies (ponds and reservoirs) in its basin [15, 21–25] (Table 1), which perform important water management functions, including ensuring the economic and drinking water supply of the cities of Kryvyi Rih and Zhovti Vody, receiving return waters of mining enterprises of Kryvyi Rih and supporting the Ingulets irrigation system [26, 27]. The river's regulation coefficient is 81 %, which indicates a significant impact of ponds and reservoirs on the hydrological regime of the river [27].

The climatic conditions of the Ingulets river basin are formed under the influence of a complex set of both general and local climate-forming factors [2]: solar radiation, air circulation, and the influence of the Earth surface. Precipitation for the entire basin is mainly associated with the activity of cyclones, to a lesser extent with the processes of intramass convection. During the year, about 450 mm of precipitation is recorded in the Ingulets river basin. The largest amount of precipitation is in June, the smallest is in February – March and September – October. Between periods of precipitation in the warm part of the year, long periods of drought are often observed.

There are several important reservoirs in the Ingulets river basin, such as Oleksandriyske (Voynivske), Iskrivske, and Karachunivske. Due to the water shortage in the Ingulets river basin, additional water is being supplied through the Dnipro-Ingulets canal along the riverbed to refill them for the local needs.

To calculate evaporation from the water surface [15, 21–25], the area of water bodies

1. Reservoirs and ponds in the Inhulets river basin

Kirovohrad region			Dnipropetrovsk region			Mykolaiv region			Kherson region		
quantity, pcs.	area, ha	volume, mln m^3	quantity, pcs.	area, ha	volume, mln m^3	quantity, pcs.	area, ha	volume, mln m^3	quantity, pcs.	area, ha	volume, mln m^3
reservoirs											
17	2646,0	81,8	4	6330,0	388,8	–	–	–	–	–	–
ponds											
502	4443,0	51,3	594	2787,0	39,9	22	234,0	2,6	94	546,7	8,8

in the Inhulets river basin and their volumes in the Kirovohrad, Dnipropetrovsk, Mykolaiv, and Kherson regions of Ukraine were determined (Table 1).

There are 1212 ponds in the Ingulets river basin (Table 1), which is 98 % of the total number of artificial water bodies; the area of the water surface in reservoirs is 8976 hectares (55 %), in ponds – 7230,0 hectares (45 %); the volume of water in the largest reservoirs – 573,2 million m^3 (86 %), in the ponds – 91,2 million m^3 (14 %). Evaporation from the surface of these reservoirs leads to water resources losses, which requires analysis.

Materials and research methods. According to the recommendations of the WMO (World Meteorological Organization) [28] and the IPCC (Intergovernmental Panel on Climate Change) [29], the current climate changes trends are assessed based on at least a 30-year period of continuous meteorological observations [30]. Typically, the base period for comparison is the period 1961–1990, which is considered as the climatic norm [30]. However, as new data sets accumulate annually, leading international expert groups for climate change assessments use other reference periods – 1981–2010 and 1991–2020 [30], since these periods also covered by the satellite data, along with the results of ground-based measurements at weather stations.

The used sources of meteorological data for the studied area of the Inhulets river basin are the archival data of meteorological observations [31] and the archives of the international Spanish meteorological site Globalclimatemonitor [32] from 1961 to 2023 period, and interpolated data according to the location of meteorological stations in the Inhulets river basin (Bashtanka, Velyka Oleksandrivka, Dolynska, Znamyanka, Komisarivka, Kryvyi Rih, Loskharivka) (Fig. 1).

In general, mathematical models used to calculate evaporation from water surface can be divided into aerodynamic models, energy balance models, water balance models, complex models, radiation-temperature models, temperature models, and models based on empirical formulae [33]. The Dalton's model is the predecessor of the mass transfer equation for estimating evaporation in open water bodies [33]. It is one of the most widely used model for calculating evaporation from a free water surface [33]. Observations of evaporation from water surface in Ukraine have significantly decreased compared to the 1950s – 1960s (36 observation points are equipped with DGI-3000 evaporators (previously there were 59), and 7 with evaporation basins (previously there were 14)) [4, 10]. Therefore, focusing on data from weather stations with existing evaporation basins or DGI-3000 evaporators, it is possible to obtain significant errors compared to using data on relative air humidity at weather stations in the Ingulets river basin. To quickly determine the water temperature for the Kakhovka reservoir, a graphical and analytical dependency on the average monthly air temperature was obtained [34]. It has been found [10] that the main factor in the current increase in evaporation is the increase in water temperature, which is accompanied by a significant increase in the partial pressure of saturated water vapor.

M.M. Ivanov found, O.R. Konstantinov developed and recommended [5] to use the connections of evaporation with the average monthly temperature and relative humidity of the air, as the most convenient for practical use, when determining evaporation from water surface, which do not require the introduction of additional corrections. Penman [7–9] proposed an equation for determining evaporation from water surface using the temperature at a height of 2 m.

So, evaporation from the surface of water bodies for specific months, seasons, and years is calculated using empirical formulae or graphs based on meteorological data (temperature and relative humidity, wind speed). Based on the above-mentioned, the evaporation rates from the surface of water bodies were determined using the formula refined by A.I. Shereshevsky [4]:

$$E = 0{,}37\, n\, (e_0 - e_{200})\, (1 + 0{,}14\, V_{200}) \quad (1)$$

where E is the evaporation (mm) per month;

$e_0 - e_{200}$ is the average monthly value of the difference between the elasticity of saturated water vapor (partial pressure of saturated water vapor) (mBar) and the elasticity (partial pressure of water vapor) of water vapor in the air (mBar) at a height of 200 cm;

V_{200} is the average monthly wind speed (m/s) at a height of 200 cm;

n is the number of days in a month.

The pressure of saturated water vapor is determined by the formula obtained by generalizing the tables of its dependence on temperature (Fig. 2, formula 2):

$$e_0 = 0{,}0436t^3 + 1{,}2442t^2 + 43{,}523t + 613{,}53, \text{ Pa}, \quad (2)$$

where t is the air temperature, °C.

At a height of 2 m (200 cm), the partial pressure of water vapor is found by formula 3, using the data on relative humidity [35].

$$e_{200} = \frac{e_0}{100} \quad (3)$$

where φ is the relative air humidity, %;

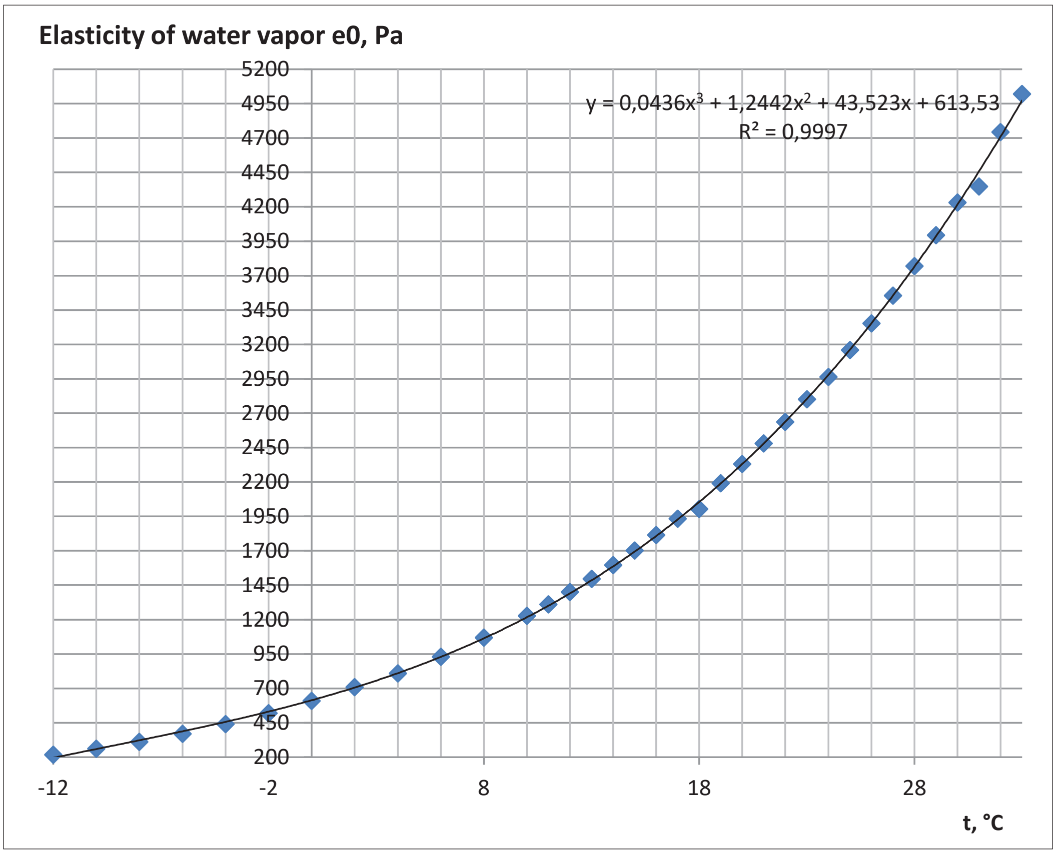


Fig. 2. Dependence of the elasticity of saturated vapor on air temperature (t, °C; e_0, Pa)

Relative air humidity and average monthly wind speed for the studied period are taken from the reference data [35], air temperature values are taken from meteorological archives [31, 32] for each of the weather stations of the Hydromet network located in the Inhulets river basin.

Research results.

Climate change in the Ingulets river basin. To characterize the climatic conditions in the Inhulets river basin over the past 63 years, data from 7 weather stations of the Ukrainian Hydrometeorological Center network were used: Bashtanka, Velyka Oleksandrivka, Dolynska, Znamenka, Komisarivka, Kryvyi Rih, Loskharivka.

The average annual air temperature in the Ingulets River basin in 1961–1990 was stable (average 8.6 °C), with minor fluctuations (Fig. 3). Data for the period of 1991–2023 confirm a sharp trend towards an increase in the average annual temperature to 9.9 °C, which is 1.3 °C more than the previous 1961–1990 period. This trend is especially noticeable after 2010. There are also significant increases in average monthly multi-year temperatures throughout the year – from 0.7 (April–May) to 2.0 (August) and 2.2 °C (January) (Fig. 4).

The average annual precipitation in the Ingulets river basin in 1961–1990 was 483.2 mm, and in 1991–2023 it decreased by almost 10 mm (473.1 mm). The distribution of precipitation during the year changed by season becoming more uneven.

Temperature changes and uneven precipitation have a very negative impact on the water regime of the Ingulets river and require further study and monitoring to promote the adaptation of this river to climate changes.

Calculation of evaporation from the surface of water bodies in the Ingulets river basin. To substantiate the elements of the balance model [36] when implementing integrated water resources management according to the basin principle, an important element is the determination of water loss for total evaporation from the surface of water bodies (ponds and reservoirs) in the Ingulets river basin.

To calculate evaporation from the surface of water bodies, detailed data on the areas of ponds and reservoirs are required (the authors have summarized these data in Table 2) as well as the local monthly climatic indicators of the region according to weather stations (Bashtanka, Velyka Oleksandrivka, Dolynska, Znamyanka, Komisarivka, Kryvyi Rih, Loskharivka).

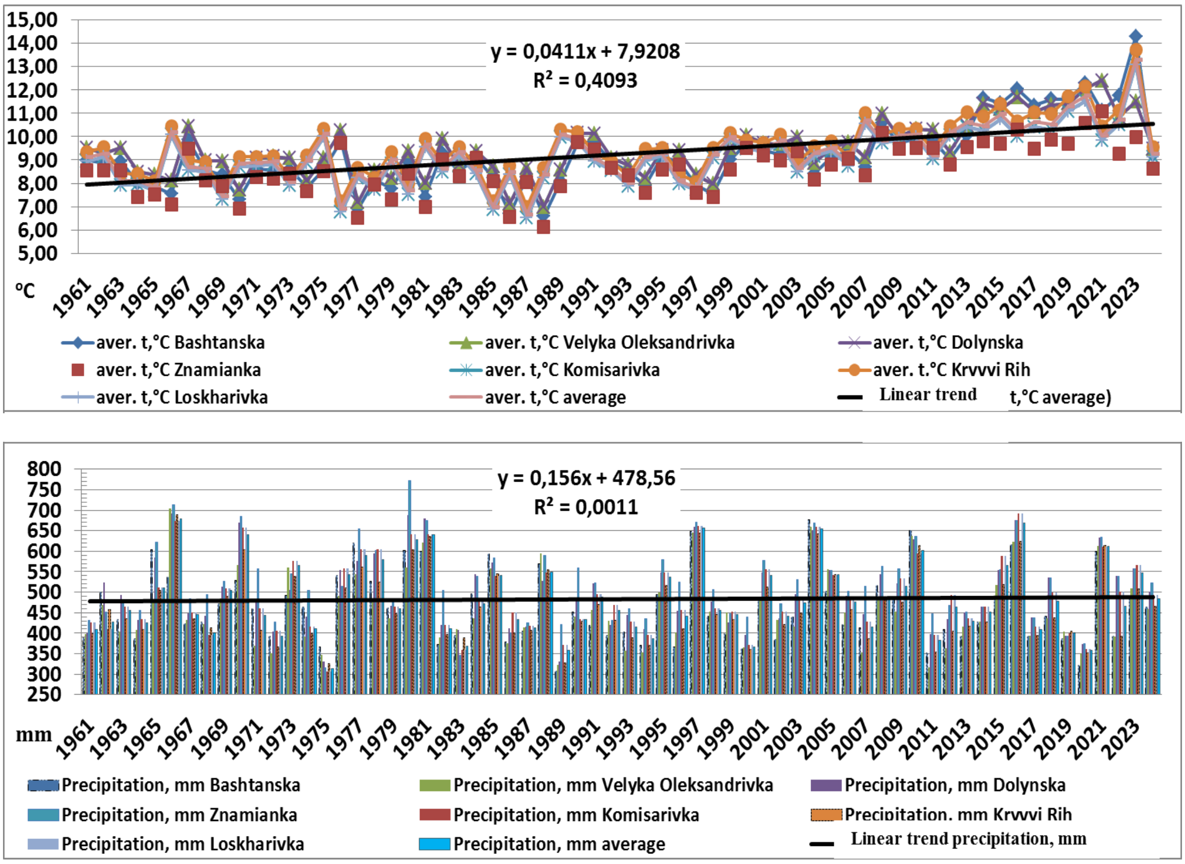


Fig. 3. Average annual dynamics of precipitation and temperature in the Ingulets river basin for the period 1961–2023

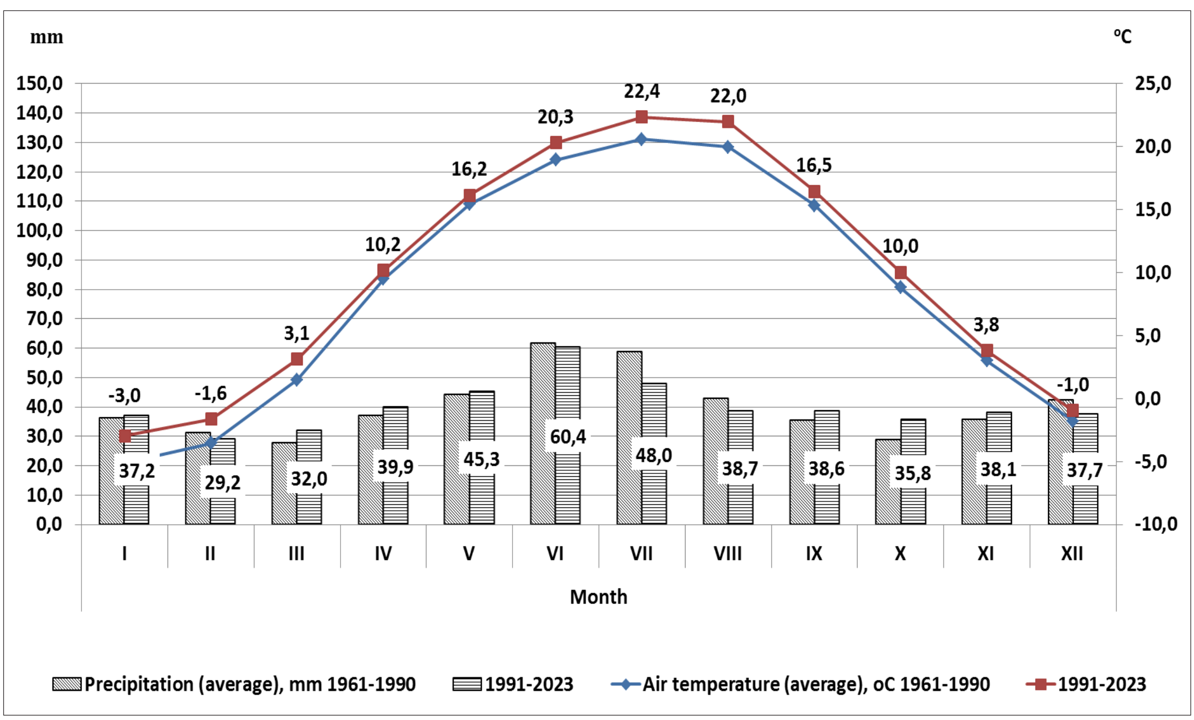


Fig. 4. Average monthly dynamics of precipitation and temperature in the Ingulets River basin for the following periods: 1961–1990 (norm), and 1991–2023

2. Calculation of evaporation from the surface of reservoirs with a volume of more than 10 million m³ and some smaller ones within the Ingulets River basin with a water surface area of more than 100 hectares

Name of reservoir, river (basin)	Location of the reservoir (settlement, region), weather station	Evaporation, mm		Area of reservoir, ha	Volume of reservoir		Evaporation, thousand m³	
		norm (1961–1990)	calculated (1991–2023)		total, mln m³	useful, mln m³	norm (1961–1990)	calculated (1991–2023)
Iskrivske, Ingulets river	vil. Iskrivka, Kirovohrad region (Znamyanka, Komisarivska)	841,0	928,0	1110,0	40,7	31,0	9335,1	10300,8
Karachunivske, Inhulets river	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	972,0	1060,0	4480,0	308,5	288,5	43545,6	47488,0
Pivdenne, Bazavluk river	*Apostolivskyi, Dnipropetrovsk region (Kryvyi Rih)*	972,0	1060,0	1130,0	57,3	26,5	10983,6	11978,0
Kresivske, Saksagan river (Inhulets river, Dnipro river)	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	972,0	1060,0	520,0	10,1	7,7	5054,4	5512,0
Makortivske, Saksagan river (Inhulets river)	vil. Makorty, Dnipropetrovsk region (Komisarivka)	898,0	966,0	1330,0	57,9	53,9	11943,4	12847,8
Saksaganske, Saksagan river (Inhulets river)	Kryvyi Rih (Kryvyi Rih)	972,0	1060,0	70,0	2,6	2,1	680,4	742,0
Khrystoforivske , Bokovenka river (Inhulets river)	vil. Khrystoforivka, Dnipropetrovsk region (Kryvyi Rih)	972,0	1060,0	120,0 (area of water surface 62,0)	4 design (1,5 actual)	No data	602,64	657,2
Oleksandriyske (Voynivske) Ingulets river	*Oleksandria, Kirovohrad region (Znameyanka)*	783,0	890,0	about 200,0	6,3	No data	1566,0	1780,0
Dykivske (Inhulets river)	*vil. Dykivka, Kirovohrad region (Znamyanka)*	783,0	890,0	194,0	3,58	3,24	1519,0	1726,6
Svitlopilsky Beshka river (Inhulets river)	*vil. Svitlopil Kirovohrad region (Znamyanka)*	783,0	890,0	188,0	3,80	2,80	1472,0	1673,2
Ivanivske Beshka river (Ingulets river)	*vil. Ivanivka Kirovohrad region (Znamyanka)*	783,0	890,0	125,0	3,20	3,20	978,8	1112,5
Pogrebnyakivske Verblyuzhka river (Ingulets river)	*vil. Verblyuzhka Kirovohrad region (Znameyanka)*	783,0	890,0	188,0	8,00	7,24	1472,0	1673,2

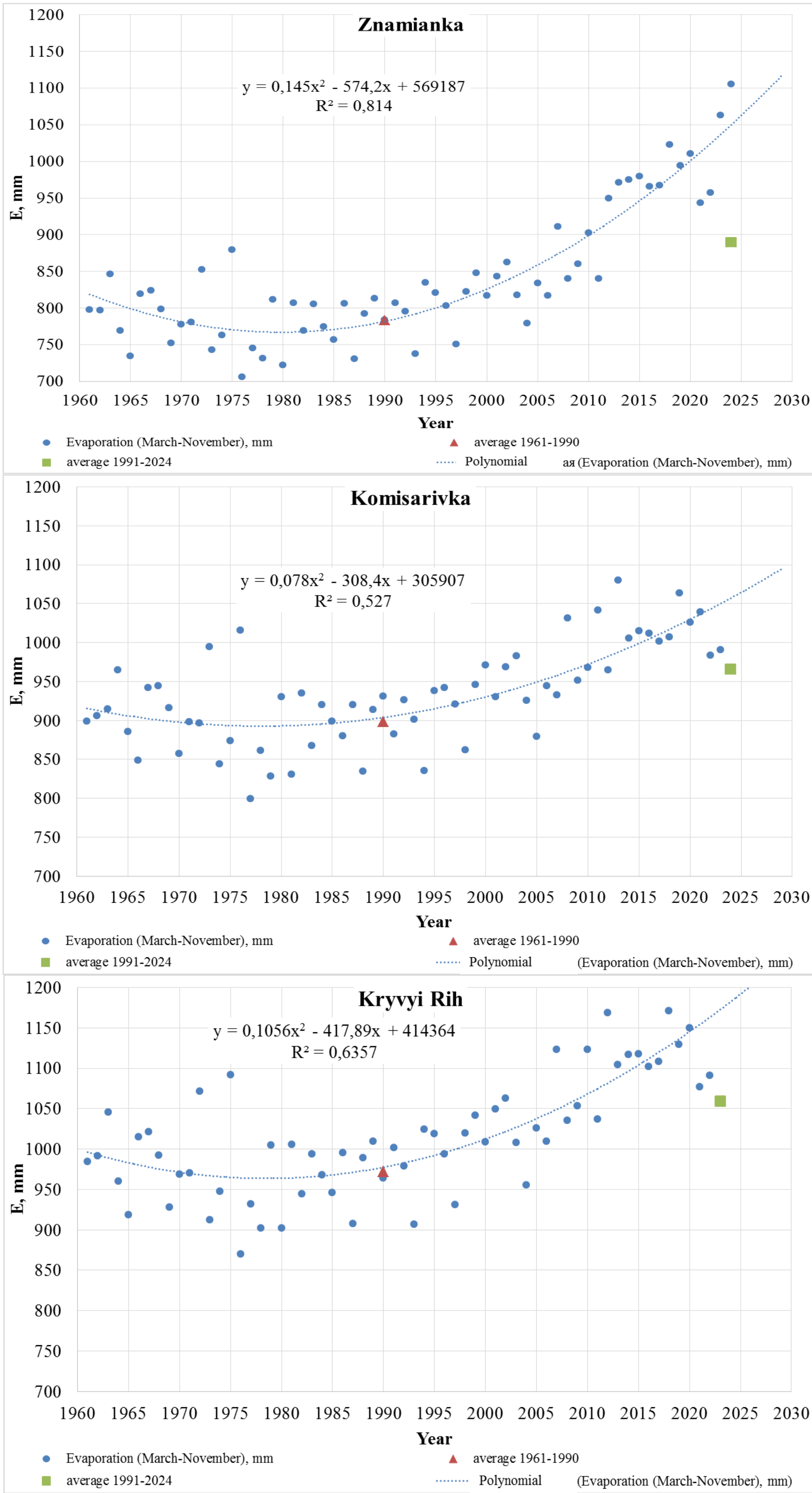


Fig. 5. Estimated evaporation for 1961–2023 period for the ice-free period (March–November) and average values for each of the two periods (1961–1990 and 1991–2023)

Before the Kakhovka HPP dam was blown up, the Pivdenne and Zelenodolsk reservoirs were supplied with water from the Dnipro-Kryvyi Rih canal. After the Kakhovka HPP was blown up, an additional load was placed on the Inhulets river, associated with ensuring water use and evaporation from the surface of the Pivdenne reservoir, where water is supplied via a pipeline from Inhulets.

It was found that the closest to the reservoirs indicated in Table 2 are the weather stations Znamyanka, Komisarivka and Kryvyi Rih (Fig. 1). For these weather stations, based on monthly weather data for the ice-free period (March-November), evaporation was calculated for 1961–1990 and 1991–2023 periods using the above-described methodology.

For each periods of 1961–1990 and 1991–2023 average values of the evaporation rate from the surface of water bodies were calculated (Fig. 5).

As calculations show (Table 2, Fig. 5), in 1991–2023, evaporation rates from the surface of water bodies increased by 13,7 % (107 mm) for the Znamyanka weather station, by 7,6 % (68 mm) for the Komisarivka weather station, and by 9,1 % (88 mm) for the Kryvyi Rih weather station.

Approximate estimates of the volume of evaporation from the surface of reservoirs in the Ingulets river basin were obtained by multiplying the area by the average long-term rate of evaporation from the surface of these reservoirs. Calculations of evaporation for reservoirs with a volume of more than 10 million m³ and some smaller ones within the Ingulets river basin are given in Table 2.

It was determined that in 1991–2023 period the average evaporation from the surface of reservoirs in the Ingulets river basin was approximately 97,5 million m³/year, which is 9,35 % higher than the norm (1961–1990).

According to rough estimates, evaporation from the water surface of ponds in the Ingulets river basin may be 70,2 million m³/year, according to the area of their water surface given in Table 1 (7230 ha) and the average evaporation value for 1991–2023 (Fig. 5 – 972 mm), which is equivalent to evaporation from reservoirs. At the same time, the water volume of the ponds is 102,6 m³, which is almost 5 times less than the volume of the reservoirs.

Discussion of the results. Analysis of the average annual dynamics of precipitation and temperature in the Ingulets River basin for the period of 1961–2023 shows that there is a constant increase in temperature indicators (Fig. 3). The linear trend of temperature increase has an insufficiently high coefficient of determination ($R^2 = 0{,}41 < 0.5$). This indicates that there is a nonlinear trend of temperature increase over the past 63 years (Fig. 6).

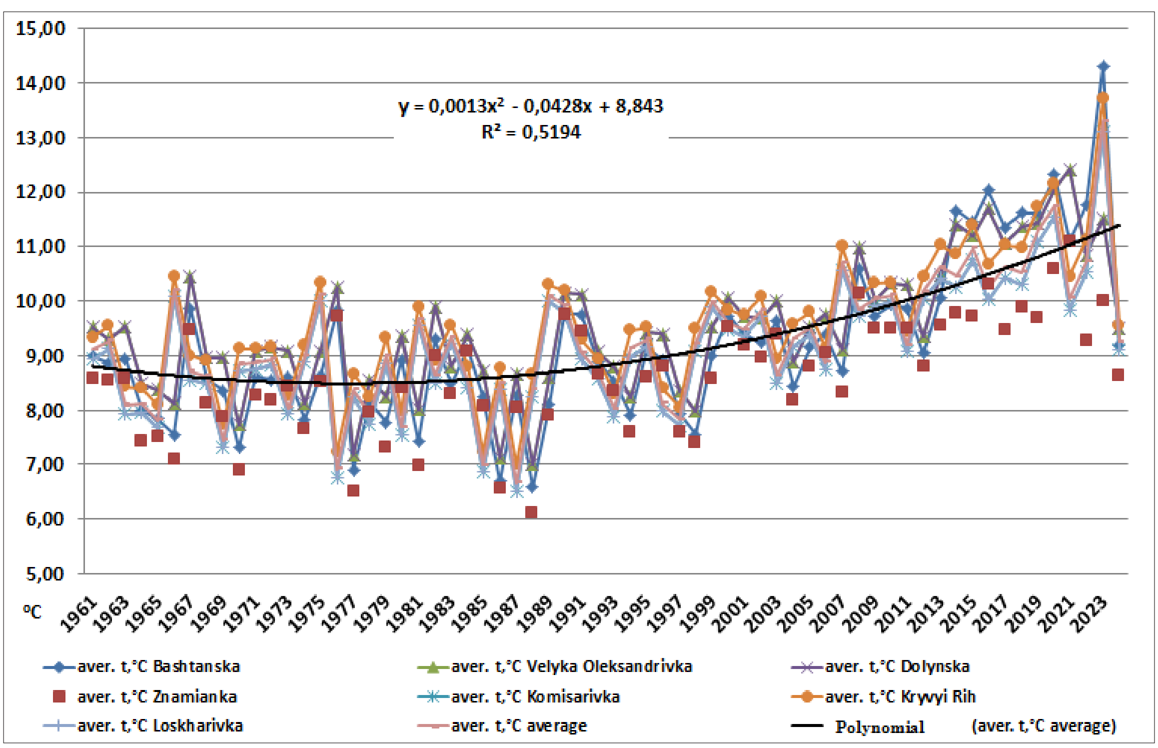


Fig. 6. Nonlinear trend of increase in average annual temperature in the Ingulets river basin

The difference between the average annual temperature values for 1961–1990 and 1991–2023 periods for weather stations in the Ingulets river basin (Fig. 7) indicates that the temperature increased by an average of 1,3 °C. In the southern part of the basin, this change is bigger, in the northern part – smaller (Fig. 1, Fig. 7).

Characterizing the dynamics of precipitation, it can be stated that the graphical analysis does not allow us to identify any long-term trend ($R^2 = 0.001$). The average long-term precipitation in the Ingulets river basin for 1961–2023 period remains at a stable level. The difference between the average annual precipitation values for 1961–1990 and 1991–2023 periods for each of the weather stations in the Ingulets River basin (Fig. 8) shows different trends in change. For example, the amount of precipitation at the Bashtanka weather station decreased by 19 mm. At the Komisarivka and Loskharivka in the northeastern part of the basin (Fig. 1) it increased by 8,5 mm (Fig. 8).

Trends in precipitation changes throughout the year (Fig. 4) show a decrease in their amount in the summer and an increase in the fall. In winter and spring, no clear trend of change is observed.

The obtained results of studies on the amount of evaporation from the surface of water bodies in the Ingulets river basin for the modern period are consistent with the normative multi-year values (Fig. 9) published on the portal "Nature of Ukraine" [37], which presents an evaporation map based on the climatic norm of 1961–1990 period. Comparison of the data obtained by the authors with cartographic norms (Table 3) showed minor deviations (up to 10 %), which confirms the correctness of the methodology and the reliability of the obtained results.

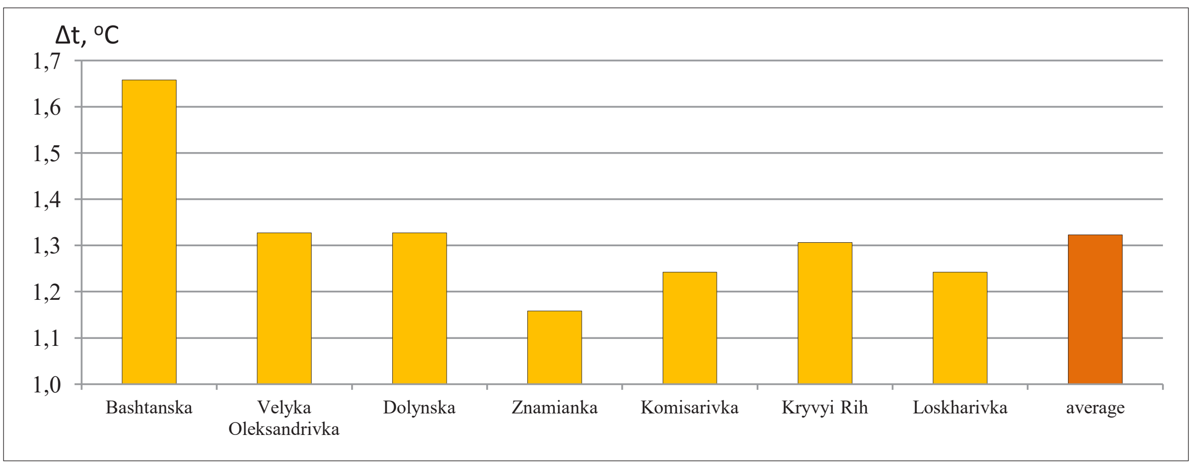


Fig. 7. Difference between average annual temperature values for 1961–1990 and 1991–2023 periods for weather stations of the Ingulets River basin

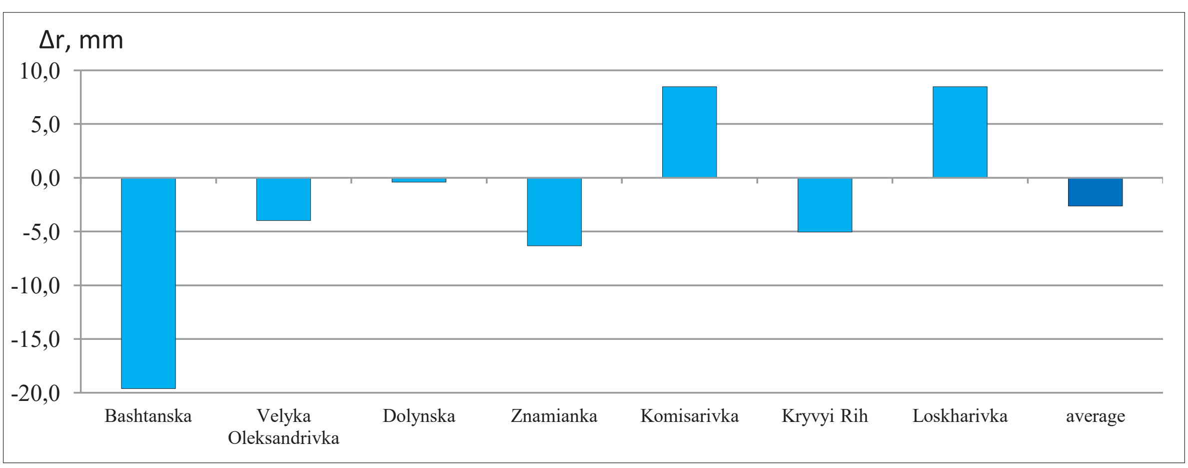


Fig. 8. Difference between average annual precipitation values for 1961–1990 and 1991–2023 periods for weather stations of the Ingulets river basin

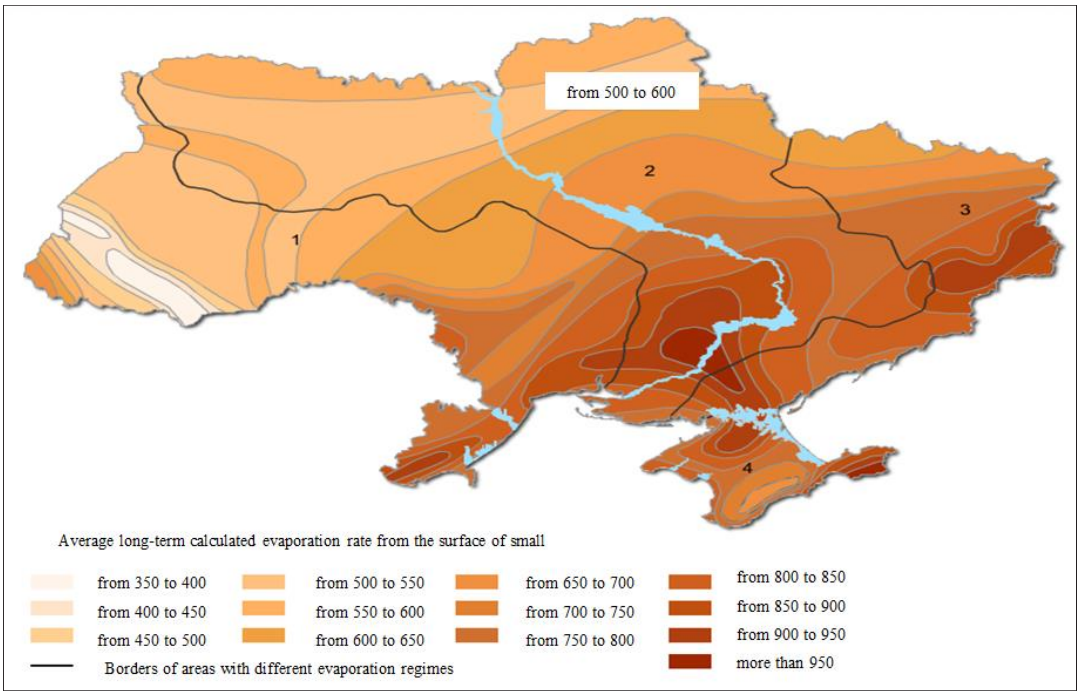


Fig. 9. Map of normative long-term values of evaporation from the surface of water bodies [37]

3. Comparison of evaporation standards for 1961–1990 period for reservoirs within the Ingulets river basin obtained from maps and calculated by the authors

Name of reservoir, river (basin)	Location of the reservoirs (settlement, region)	Evaporation rate (Fig. 9), mm	Evaporation rate (1961–1990 period), mm	Difference
Iskrivske, Ingulets river (Dnipro river)	vil. Iskrivka, Kirovohrad region (Znamyanka, Komisarivska)	750–800	841	+10…2 %
Karachunivske, Inhulets river (Dnipro river)	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	900–950	972	+8…2 %
Pivdenne*, Bazavluk river (Dnipro river)	*Apostolivskyi, Dnipropetrovsk region (Kryvyi Rih)*	>950	972	≈2 %
Kresivske, Saksagan river (Inhulets river, Dnipro river)	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	900–950	972	+8…2 %
Makortivske, Saksagan river (Inhulets river, Dnipro river)	vil. Makorty, Dnipropetrovsk region (Komisarivka)	850–900	898	+6…0 %
Saksaganske, Saksagan river (Inhulets river, Dnipro river)	Kryvyi Rih (Kryvyi Rih)	900–950	972	+8…2 %
Khrystoforivske , Bokovenka river (Inhulets river) [73]	vil. Khrystoforivka, Dnipropetrovsk region (Kryvyi Rih)	900–950	972	+8…2 %
Oleksandriyske (Voynivske) Ingulets river (Dnipro river)	*Oleksandria, Kirovohrad region (Znameyanka)*	750–800	783	+4…–2 %
Dykivske (Inhulets river, Dnipro river)	*vil. Dykivka, Kirovohrad region (Znamyanka)*	750–800	783	+4…–2 %
Svitlopilsky Beshka river (Inhulets river, Dnipro river)	*vil. Svitlopil Kirovohrad region (Znamyanka)*	750–800	783	+4…–2 %
Ivanivske, Beshka river (Ingulets river, Dnipro river)	*vil. Ivanivka Kirovohrad region (Znamyanka)*	750–800	783	+4…–2 %
Pogrebnyakivske, Verblyuzhka river (Ingulets river, Dnipro river)	*vil. Verblyuzhka Kirovohrad region (Znameyanka)*	750–800	783	+4…–2 %

*After the Kakhovka Dam was blown up it is supplied with water from the Ingulets river.

Water consumption of southern agricultural crops is increasing and will continue to increase due to the air temperatures rising [38], which is accompanied by an increased evaporation from the water surface of ponds and reservoirs [11] and is confirmed by trend analysis (Fig. 5). This, in accordance with global trends [11, 39], will lead to an increase in the demand for water resources in the Ingulets river basin.

As the average annual flow of the Ingulets river is about 0,3 km³, and water losses due to evaporation can reach up to 0,165 km³ per year, this means that they account for more than 50 % of the river's flow.

Taking into account the expected increase in the load on the surface water resources of the basin (Fig. 5), it is necessary to implement scientifically based management solutions [14], in particular, attracting additional volumes of water from the Dnipro river through the Dnipro–Inhulets canal.

According to research results, the evaporation rate from the surface of the basin's water bodies for the period 1991–2023 increased by an average of 10 % compared to the climatic norm of 1961–1990 period, which is a consequence of climate changes. Evaporation from ponds, as shown above, is proportional to losses from the surface of reservoirs. This will contribute to the increase in the deficit of water resources in the Ingulets river basin and will become a limiting factor for the development of irrigation. In order to increase the accumulation of water in existing artificial reservoirs, it is advisable to clean and deepen them, and to develop catchment and coastal areas.

Prospects for further research. The obtained results have practical significance and can be used to develop adaptation measures in response to climate changes, improve methods for assessing water losses caused by the evaporation, and develop effective water resource management strategies in river basins. It is important to take into account modern challenges, in particular, climate stress – the combined impact of long-term increases in air temperature, changes in precipitation patterns, increased frequency and duration of droughts, as well as anthropogenic stress – that is, man-made changes in the hydrological regime through the flow regulation, water abstraction, pollution, and transformation of natural ecosystems. Further research should be aimed at a comprehensive assessment of these factors to substantiate scenarios for sustainable water use under climate changes.

Conclusions. The results of the research show that the climatic conditions in the studied region confirm a steady warming trend: over the past 33 years, the average annual temperature in the Ingulets river basin has increased by an average of 1,3 °C. At the same time, water losses due to evaporation from the water surface of reservoirs and ponds in the Ingulets river basin are significant and are increasingly having an impact on the regional water balance. This is especially relevant in the context of the growing shortage of water resources associated with climate changes and infrastructure losses. The evaporation rate from the surface of ponds and reservoirs for the period 1991–2023 in the Ingulets river basin increased by an average of 10 % compared to the evaporation rate in 1961–1990 period.

The analysis confirms the dominance of artificial reservoirs (ponds and reservoirs) in the hydrological regime of the Ingulets river basin, which causes a change in natural flow (water losses due to evaporation reach approximately 0.165 km³ per year), the transformation of rivers into cascades of isolated reservoirs.

The obtained results can be used to develop programs for climate changes adaptation and form regional strategies for water resources management, in particular in emergency situations similar to the disaster caused by the destruction of the Kakhovka HPP dam.

References

1. Materialy naukovo-praktychnoyi konferentsiyi "Pryroda i voda" [Materials of the scientific and practical conference "Nature and Water]. (2018). Pryroda i voda: Naukovo-praktychna konferentsiya. Dnipro: DDAEU, 3–4 Retrieved from: https://dspace.dsau.dp.ua/bitstream/123456789/1460/1/Природа_і_вода.pdf [in Ukrainian]

2. Khil'chevs'kyy, V.K., Kravchyns'kyy, R.L., & Chunar'ov, O.V. (2012). Hidrokhimichnyy rezhym ta yakist' vody Inhul'tsya v umovakh tekhnohenezu [Hydrochemical regime and water quality of Ingulets in conditions of technogenesis]. Kyiv: Nika-Tsentr, 180. Retrieved from: https://geo.knu.ua/wp-content/uploads/2025/01/hilchevskyj-vk.-ta-in._gidrohim.-rezhym-ingulczya.pdf [in Ukrainian]

3. Zhao, G., Gao, H., & Kao, S. C. (2021). The implications of future climate change on the blue water footprint of hydropower in the contiguous US. *Environmental Research Letters*, 16 (3), 034003. DOI 10.1088/1748-9326/abd78d.

4. Shereshevs'kyy, A.I., & Synyts'ka L.K. (2003). Rozrakhunkove vyparovuvannya z vodnoyi poverkhni na terytoriyi Ukrayiny [Estimated evaporation from the water surface on the territory of Ukraine]. *Naukovi Pratsi UkrNDHMI*, 252, 11–26 [in Ukrainian]

5. Hryb, O.M. (2014). Otsinka vyparovuvannya z vodnoyi poverkhni v rayoni Tylihul's'koho lymanu [Estimation of evaporation from water surfaces in the Tiligul estuary area]. *Visnyk Odes'koho derzhavnoho ekolohichnoho universytetu*, 17, 173–184. Retrieved from: http://nbuv.gov.ua/UJRN/Vodeu_2014_17_21 [in Ukrainian]

6. Béchet, Q., Sialve, B., Steyer, J. P., Shilton, A., & Guieysse, B. (2018). Comparative assessment of evaporation models in algal ponds. *Algal Research*, 35, 283–291.

7. Jensen M.E. (2010). Estimating evaporation from water surfaces. In *CSU/ARS Evapotranspiration Workshop, Fort Collins, CO*, 1–27. Retrieved from: https://www.researchgate.net/publication/265749992_Estimating_evaporation_from_water_surfaces.

8. Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London*, 120–146.

9. Penman, H.L. 1963. Vegetation and hydrology. *Tech. Comm.*, 53. Commonwealth Bureau of Soils, Harpenden, England. 125 p.

10. Vyshnevs'kyy, V. (2022). Vplyv zminy klimatu na vyparovuvannya z poverkhni vody v Ukrayini [The impact of climate change on evaporation from water surfaces in Ukraine]. *Zhurnal heolohiyi, heohrafiyi ta heoekolohiyi*, 31 (1), 163–170. Retrieved from: https://doi.org/https://doi.org/10.15421/112216 [in Ukrainian]

11. Zhou, Y., Dong, J., Cui, Y., Zhou, S., Li, Z., Wang, X., & Xiao, X. (2022). Rapid surface water expansion due to increasing artificial reservoirs and aquaculture ponds in North China Plain. *Journal of Hydrology*, 608, 127637. Retrieved from: https://doi.org/10.1016/j.jhydrol.2022.127637.

12. Korbutyak, V. M., & Stefanyshyn, D. V. (2018) Transformatsiyi minimal'noho stoku r. Sluch ta yikh vplyv na Novohrad-Volyns'ke vodoskhovyshche yak ob″yekt mistsevoyi krytychnoyi infrastruktury [Transformations of the minimum flow of the Sluch River and their impact on the Novograd-Volynske reservoir as an object of local critical infrastructure]. *Matematychne modelyuvannya v ekonomitsi*, 4, 70–81. Retrieved from: http://nbuv.gov.ua/UJRN/mmve_2018_4_8 [in Ukrainian]

13. Rudakov, L.M., Hapich, H.V., & Chushkina, I.V. (2017). Vyznachennya vtrat vody na vyparovuvannya z vodnoyi poverkhni rehulyuyuchykh baseyniv zroshuval'nykh merezh [Determination of water losses due to evaporation from the water surface of regulating basins of irrigation networks]. Vdoskonalennya hidrotekhnichnykh system ta vodohospodars'kykh tekhnolohiy. Materialy mizhnar. nauk.-prakt. konferentsiyi. Kherson: Vyd-vo PP "LT – Ofis", 176–179. Retrieved from: http://dspace.dsau.dp.ua/jspui/handle/123456789/1442 [in Ukrainian].

14. Andreev, V. H., & Hapich, H.V. (2020). Vplyv budivnytstva stavkiv i vodoskhovyshch na ekolohichnu bezpeku baseyniv malykh richok stepovoyi zony Ukrayiny (na prykladi Dnipropetrovs'koyi oblasti) [The impact of the construction of ponds and reservoirs on the ecological safety of small river basins of the steppe zone of Ukraine (on the example of the Dnipropetrovsk region)]. *Melioratsiya i vodne hospodarstvo*, 1, 158–166. Retrieved from: http://nbuv.gov.ua/UJRN/Mivg_2020_1_18 [in Ukrainian].

15. Hrebin', V.V., Khil'chevs'kyy, V.K., Stashuk, V.A., Chunar'ov, O.V., & Yaroshevych, O.YE. (2014). Vodnyy fond Ukrayiny: Shtuchni vodoymy – vodoskhovyshcha i stavky: Dovidnyk [Water Fund of Ukraine: Artificial Water Reservoirs – Reservoirs and Ponds: Handbook]. Kyiv: "Inter-pres LTD" [in Ukrainian].

16. Stashuk, V.A., Morozov, V.V., & Ladyky, M.M. (2010). Melioratsiya vody i ahrolandshaftiv v baseyni r. Inhulets': Monohrafiya [Land Reclamation of Water and Agricultural Landscapes in the Ingulets River Basin: Monograph]. Kherson: Vyd-vo "Aylant" [in Ukrainian].

17. Rehlament promyvannya rusla ta ekolohichnoho ozdorovlennya r. Inhulets' u 2019 rotsi (Al'ternatyvnyy variant) [Regulations for the washing of the riverbed and ecological improvement of the Ingulets River in 2019 (Alternative version)]. (2019). Kyiv: PrAT "Ukrvodproekt" [in Ukrainian].

18. Shumilova, O., Sukhodolov, A., Osadcha, N., Oreshchenko, A., Constantinescu, G., Afanasyev, S., & Grossart, H. P. (2025). *Environmental effects of the Kakhovka Dam destruction by warfare in Ukraine. Science*, 387 (6739), 1181–1186. DOI: 10.1126/science.adn8655.

19. Cabinet of Ministers of Ukraine. (2024). Derzhavna tsil'ova prohrama kompleksnoho vodozabezpechennya terytoriy, yaki zaznaly vplyvu voyennykh diy, na period do 2030 roku Derzhavna tsil'ova prohrama [State Target Program for Comprehensive Water Supply of Territories Affected by Military

Actions for the Period Until 2030 State Target Program]. Kyiv: State Agency of Water Resources of Ukraine. Retrieved from: https://davr.gov.ua › fls18 › watersupplyprogram [in Ukrainian].

20. Murashko, A. (2024). Pidryv Kakhovs'koyi HES: budivnytstvo mahistral'noho vodohonu "Inhulets' – Pivdenne vodoskhovyshche" zaversheno [Kahovka blown up: construction of the Ingulets – Pivdenne Reservoir water main completed]. Ukrainian National News. Retrieved from: https://unn.ua/news/pidryv-kakhovskoi-hes-budivnytstvo-mahistralnoho-vodohonu-inhulets-pivdenne-vodoskhovyshche-zaversheno [in Ukrainian].

21. Palamarchuk, M.M., & Zakorchevna, N.B. (2006). Vodnyy fond Ukrayiny: Dovidkovyy posibnyk [The Water Fund of Ukraine: Reference Manual]. 2-e vyd. [2nd ed.]. Kyiv: Nika-Tsentr. 320 [in Ukrainian].

22. Cabinet of Ministers of Ukraine. (2024). Plan upravlinnya richkovym baseynom Dnipra [Dnieper River Basin Management Plan]. State Agency of Water Resources of Ukraine. Retrieved from: https://davr.gov.ua/fls18/PURBDnipro.pdf [in Ukrainian].

23. Derzhavnyy vodnyy kadastr: oblik poverkhnevykh vodnykh ob'yektiv [State Water Cadastre: Accounting for Surface Water Bodies]. www.geoportal.davr.gov.ua Retrieved from: https://geoportal.davr.gov.ua/#arraysSurfaceWatersSidebar [in Ukrainian]

24. Monitorynh ta ekolohichna otsinka vodnykh resursiv Ukrayiny [Monitoring and ecological assessment of water resources of Ukraine]. www.monitoring.davr.gov.ua Retrieved from: http://monitoring.davr.gov.ua/EcoWaterMon/GDKMap/Index.

25. Kryvul'chenko, A.I., Fomenko, R.P., & Naumenko, N.V. (1999). Fond vodoskhovyshch Kirovohrads'koyi oblasti, holovni osoblyvosti ta zakonomirnosti poshyrennya [Reservoir Fund of Kirovohrad Region, Main Features and Distribution Patterns]. Regional geographical studies: Scientific news. Kirovohr[in Ukrainian]ad: Regional Research Center of V. Vynnychenko Kyiv State Pedagogical University, 26–35.

26. Kovalchuk, V., Kovalchuk, P., Yatsyuk, M., Kovalenko, R., Demchuk, O., & Balykhina, H. (2020). System model of integrated management of the water resources of the Ingulets River by a basin principal. *Land Reclamation and Water Management*, (1), 37–48. DOI: https://doi.org/10.31073/mivg202001-219 [in Ukrainian].

27. Khil'chevs'kyy, V.K. Inhulets'. Velyka ukrayins'ka entsyklopediya [Great Ukrainian Encyclopedia]. www.vue.gov.ua. Retrieved from: https://vue.gov.ua/Інгулець. [in Ukrainian]

28. World Meteorological Organization (WMO). www.wmo.int. Retrieved from: https://wmo.int

29. Intergovernmental Panel on Climate Change (IPCC). www.ipcc.ch. Retrieved from: https://www.ipcc.ch

30. Metodychni rekomendatsiyi shchodo vrakhuvannya klimatychnoho komponenta pid chas zdiysnennya otsinky vplyvu na dovkillya [Methodological recommendations for taking into account the climate component when assessing the impact on the environment]. (2024). Kyiv: Ministry of Environmental Protection and Natural Resources of Ukraine. Retrieved from: https://mepr.gov.ua/wp-content/uploads/2024/10/1382nd2.docx [in Ukrainian]

31. Freemeteo. www. freemeteo.com.ua. Retrieved from: freemeteo.com.ua

32. Mizhnarodnyy ispans'kyy meteosayt Globalclimatemonitor [International Spanish weather website Globalclimatemonitor]. Retrieved from: https://www.globalclimatemonitor.org [in Ukrainian].

33. Zhang, S., Chen J., Du, Q., Xue, J., Yang, X. (2024). Energy conversion for water surface evaporation in evaporation ponds with different depths and improvement of Dalton model. *Journal of Hydrology*, Vol. 644, 132094. https://doi.org/10.1016/j.jhydrol.2024.132094.

34. Obukhov, Ye. V. (2014). Uzahal'nennya zalezhnostey mizh hidrometeorolohichnymy kharakterystykamy v rayoni Kakhovs'koho vodoskhovyshcha dlya vyznachennya vyparovuvannya z yoho vodnoyi poverkhni [Generalization of dependencies between hydrometeorological characteristics in the area of the Kakhovka reservoir to determine evaporation from its water surface]. *Ukrayins'kyy hidrometeorolohichnyy zhurnal*, 15, 141–148. Retrieved from: http://nbuv.gov.ua/UJRN/Uggj_2014_15_22 [in Ukrainian].

35. Klimatychnyy kadastr Ukrayiny (2006). Derzhavna hidrometeorolohichna sluzhba UkrNDHMI. Tsentral'na heofizychna observatoriya [in Ukrainian].

36. Koval'chuk, V.P., Yatsyuk, M.V., Nechay, O.M., Balykhina, H.A. (2025). Stsenarnyy analiz i porivnyannya variantiv utylizatsiyi shakhtnykh vod zi stavkiv-nakopychuvachiv. [Scenario analysis and comparison of options for disposal of mine water from storage ponds.]. Zbirnyk tez XIII Mizhnarodnoyi naukovo-praktychnoyi konferentsiyi "Voda dlya maybutn'oho: upravlinnya,

zberezhennya, innovatsiyi", prysvyachenoyi Vsesvitn'omu dnyu vodnykh resursiv, Kyyiv: IVPiM NAAN, 68-71. DOI: https://doi.org/10.31073/mivg2025 [in Ukrainian].

37. Portal "Pryroda Ukrayiny". Richky Ukrayiny. river.land.kiev.ua. Retrieved from: https://river.land.kiev.ua/annual-flow.html [in Ukrainian].

38. Kovalchuk, V. P., Balykhina, H. A., Kovalchuk, P. I., Yatsiuk, M. V., Voitovych, O. P., & Demchuk D. O. (2025). Managing Irrigation Systems under Climate Change: Assessing Crop Water Demand and Developing Water-Saving Solutions. In: Irrigation Management: Strategies, Sustainability and Agricultural Advancements. Editors: Maha Elbana and Youssef Brouziyne. NY: Nova Science Publishers, Inc., pp.37-70. DOI: https://doi.org/10.52305/UQGT5734 [in Ukrainian]

39. Zou, Z., Dong, J., Menarguez, M. A., Xiao, X., Qin, Y., Doughty, R.B., Hooker, K., & Hambright, K. D. (2017). Continued decrease of open surface water body area in Oklahoma during 1984–2015. *Science of The Total Environment*, 595, 451-460. https://doi.org/10.1016/j.scitotenv.2017.03.259

УДК: 556.5:551.58

ОЦІНЮВАННЯ ВИТРАТ ВОДИ НА СУМАРНЕ ВИПАРОВУВАННЯ З ПОВЕРХНІ СТАВКІВ І ВОДОСХОВИЩ У БАСЕЙНІ Р. ІНГУЛЕЦЬ

В.П. Ковальчук[1], докт. техн. наук, О.М. Нечай[2], канд. с.г. наук, Г.А. Балихіна[3], канд. техн. наук, О.П. Войтович[4], Ph.D.

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0001-7570-1264, e-mail: volokovalchuk@gmail.com;
[2] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0003-0365-1864; e-mail: water_2019@ukr.net;
[3] Національна академія аграрних наук України, Київ, Україна;
https://orcid.org/0000-0002-5571-3556, e-mail: maslova-anna@ukr.net;
[4] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-1513-4744; e-mail: aleksvoitovych@gmail.com ;

Анотація: *У статті розглядається проблема втрат води на випаровування з поверхні ставків і водосховищ в умовах інтенсивного антропогенного навантаження та кліматичних змін, зосереджуючись на басейні річки Інгулець як прикладу однієї з найбільш зарегульованої річкової системи степової зони України. З огляду на зростаючий дефіцит водних ресурсів, особливо після підриву Каховської ГЕС, актуальність дослідження випаровування з водних поверхонь штучних водойм південних регіонів зростає. Оцінка втрат води через випаровування з поверхні ставків і водосховищ у басейні річки Інгулець є важливим аспектом управління водними ресурсами регіону. Використано доступні дані про площі штучних водних об'єктів та середні норми випаровування для розрахунку загальних втрат води. На основі просторового аналізу понад 1200 водних об'єктів у басейні р. Інгулець, включаючи оцінку площ та об'ємів водосховищ і ставків, здійснено кількісну оцінку випаровування води з їх поверхні за 1961–1990 рр та 1991–2023 рр. Методологія дослідження ґрунтується на обробці багаторічних метеорологічних даних з локальних метеостанцій, а також на використанні супутникової та архівної інформації з доступних сайтів. Кліматичні умови в регіоні дослідження демонструють сталу тенденцію до потепління: за останні 30 років середньорічна температура в басейні р. Інгулець зросла в середньому на 1,3 °С при незначних зменшеннях опадів за досліджуваний період. Встановлено, що в сучасних умовах процес випаровування може перевищувати надходження з атмосферних опадів, що перетворює штучні водойми на активні чинники зменшення водного балансу басейну річки Інгулець. У 1991–2023 рр норми випаровування з поверхні водойм зросли на 13,7 % (107 мм) для метеостанції Знам'янка, для метеостанції Комісарівка – 7,6 % (68 мм) та для метеостанції Кривий Ріг на 9,1 % (88 мм). Особлива увага приділяється оцінці водогосподарської ефективності функціонування таких об'єктів у контексті екологічної безпеки, гідрологічної стабільності та адаптації до змін клімату. Отримані результати мають важливе значення для розробки регіональних стратегій управління водними ресурсами, удосконалення методів розрахунку втрат води та еколого-економічної оптимізації структури водного фонду у басейнах малих та середніх річок.*

Ключові слова: *басейн р. Інгулець, випаровування, зміна клімату, штучні об'єкти, ставки та водосховища, водний баланс, управління водними ресурсами*

DOI: https://doi.org/10.31073/mivg202501-419
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/419

UDC 332.142.6:504:556

IDENTIFICATION METHOD FOR THE LEVEL OF ENVIRONMENTAL SAFETY OF WATER BODIES

M.V. Yatsiuk[1], Dr. of Technical Sciences, S.M. Chumachenko[2], Dr. of Technical Sciences, O.O. Sydorenko[3], Ph.D. in Agricultural Sciences, O.V. Turaieva[4]

[1] Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Kyiv, 03022, Ukraine; https://orcid.org/0000-0002-5535-715X, e-mail: mv_yatsiuk@ukr.net;
[2] State Research Institute of Aviation of the Ministry of Defence of Ukraine, Kyiv, 01135, Ukraine; https://orcid.org/0000-0002-8894-4262, e-mail: sergiy23.chumachenko@gmail.com;
[3] Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Kyiv, 03022, Ukraine; https://orcid.org/0000-0002-7377-6809, e-mail: 63059@ukr.net;
[4] Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Kyiv, 03022, Ukraine; https://orcid.org/0000-0002-3367-404X, e-mail: turaieva.olga@gmail.com

Abstract. *A method for identifying the environmental safety of water bodies under conditions of uncertainty has been developed using systems analysis methods and a multicriteria approach. Improving the adequacy of identification involves searching for a more suitable criterion and using multiple criteria that comprehensively describe the goal of identifying the environmental safety level of water bodies and complement each other. The determination of environmental safety in the context of the requirements of the Water Code of Ukraine should be structured according to integrated criteria. The proposed identification method uses techniques for calculating scores of various factors that characterize the components of specific criteria. The objectivity of the identification process is ensured by using criteria that provide a sufficiently complete chain of assessment features of threats. The identification procedure is based on multicriteria evaluation approaches with subsequent aggregation into an integral index that defines the water body's environmental safety level. During the identification procedure, the values of indicators and indices of relevant characteristics are mapped to corresponding evaluation scales. The arguments of the target identification function, which are features of the evaluation factors according to their respective criteria components, are expressed as dimensionless scores. The identification problem for natural or artificial objects under uncertainty is solved using systems analysis methods and a multicriteria approach, and it is reduced to comparing the resulting scores and ranking them by a set of partial or integral criteria (index). The use of the Analytic Hierarchy Process to justify the contribution of comprehensive components to assessing the environmental safety level of Ukraine's water bodies is a key element that made it possible to select the most appropriate assessment methodology.*

Keywords: *anthropogenic load, water bodies, environmental safety, natural-technogenic geosystems*

Relevance of the research. Identifying the level of environmental safety for natural or technogenic (artificial) objects under conditions of uncertainty is addressed through systems analysis methods using a multicriteria approach.

To identify the environmental safety level of water bodies (WB), it is necessary to develop criteria not only in the narrow sense of a "criterion function" but in a broader sense, as a method for identifying the environmental safety level.

Cases where a single criterion successfully reflects the goal of identifying the environmental safety level are exceptions rather than the rule. A single criterion only approximately (as any model does) reflects the assessment objective, and its adequacy may be insufficient. Enhancing adequacy involves seeking a more appropriate criterion (which may not even exist) and applying multiple criteria that describe the objective of identifying the environmental safety level of WB from different perspectives and complement one another.

Analysis of recent research and publications. To date, the issue of defining the composition and structure of anthropogenic load factors remains insufficiently addressed in WB. As noted in publications [1–3], expert evaluation methods are commonly used for similar tasks in environmental engineering, including interval evaluation, the Analytic Hierarchy Process (AHP), stepwise matrices, and network diagrams. However, in our case – where data on the quantitative characteristics of anthropogenic load factors are lacking, and impact assessment for many factors is poorly formalized due to the absence of prior research – it is appropriate to combine methods such as stratification, cause-and-effect diagrams, the Delphi method, and Saaty's Analytic Hierarchy Process [4, 5]. Within existing resource and financial constraints, these approaches allow for the development of an effective, comprehensive method and creation of structured hierarchical trees depicting the influence of anthropogenic load factors on WB, as well as the development of information profiles for watershed and subwatershed areas.

A methodological manual [6] devotes considerable attention to classifying anthropogenic pollution sources. The classification features include the circumstances of pollution emergence, the nature of the sources, and their impact regularity. The resolution of the Cabinet of Ministers of Ukraine [7] describes the main types of water pollution and the frequency of monitoring their indicators. In the article [8], a systems approach is used to generalize anthropogenic load factors that may be applied in developing a systemic classification of sources and factors of anthropogenic load.

The aim of the research is to develop a method for identifying WB's environmental safety level using techniques for calculating point-based evaluations of various factors characterizing the individual components of specific criteria.

Materials and research methods. The objectivity of solving the task of identifying the environmental safety level of WB is ensured through the application of criteria that provide a sufficiently comprehensive chain for evaluating threat indicators. This means the requirements must cover all critical aspects of the evaluation objective while minimizing their total number. This latter requirement is satisfied when the criteria are independent and not interconnected (e.g., it is preferable not to use identical measured values or values derived from one another in different criteria components) [9].

Identifying the environmental safety level of WB utilizes techniques for calculating point-based assessments of various factors representing specific criteria components. A hierarchical structural-logical scheme of criteria and factors is shown in Figure 1.

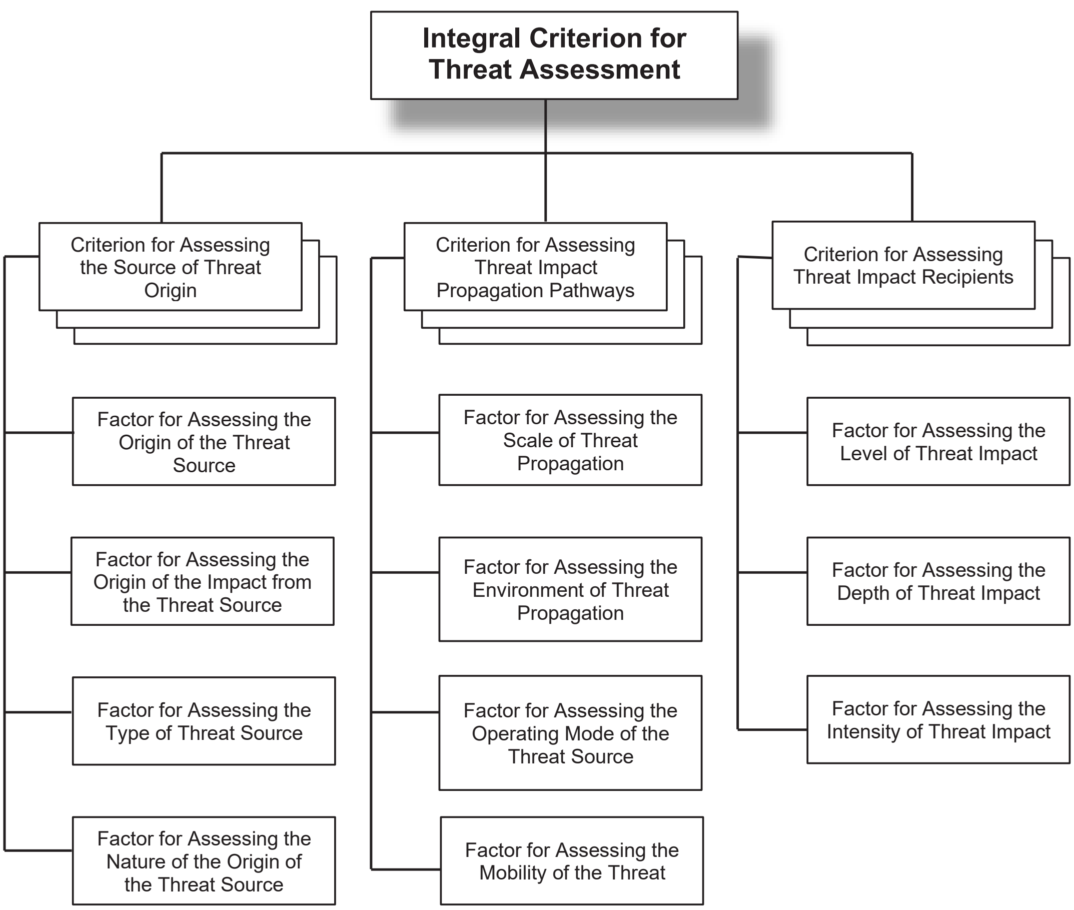


Fig. 1. Hierarchical structural and logical diagram of criteria and factors for identifying water bodies' environmental safety level

The comprehensive assessment procedure is based on multicriteria threat evaluation approaches, which are then aggregated into an integral index. This approach generally acquires practical significance only when the multicriteria task is reduced to a single-criterion one. However, the advantages of combining multiple criteria into a super-criterion come with specific difficulties and drawbacks that must be considered when applying this method.

The impact of anthropogenic load factors leads to the pollution of the components of the geospheres of natural-technological geosystems. Pollution of natural-technological geosystems should be understood as a change in the properties of its geosphere components (chemical, mechanical, physical, biological, and related informational properties), which occurs as a result of the action of anthropogenic load factors that cause the deterioration of the functions of aquatic ecosystems concerning living objects of the biosphere (humans, biological organisms, biocenosis, etc.).

A comparative analysis of existing classifications of technogenic load and the generalization of experience in this field of applied ecology allows the formation of the following classification features of anthropogenic load:

– nature of origin;
– type of origin;
– sphere of distribution;
– scale of distribution;
– type of source;
– operating mode of the source.

By the above approaches, a compilation of the characteristics of factors, partial and integral criteria, is carried out (Table 1). Based on this approach, the generalized additive and multiplicative objective functions can be represented as follows:

$$J_{\Sigma}(e) = \sum_{i=1}^{n} \frac{\alpha_i}{s_i} J_i(e_i), \quad (1)$$

$$J_{\Pi}(e) = \prod_{i=1}^{n} \frac{\alpha_i}{s_i} J_i(e_i), \quad (2)$$

where α_i and s_i are weighting coefficients that can be determined by expert judgment, for example, using the AHP procedures.

1. Classification of Criteria and Factors for Identifying the Level of Environmental Safety of Water Bodies

Criterion for assessing the source of the threat						
1. Factor for assessing the origin of the threat source						
Military actions	Global climate change	Emergencies	Industrial activity	Agricultural activity		
2. Factor for assessing the origin of the threat source						
Radioactive	Chemical	Electromagnetic	Mechanical	Acoustic	Vibrational	Thermal
3. Factor for assessing the type of threat source						
Unorganized	Organized	Group	Single	Planar	Point	
4. Factor for assessing the nature of the origin of the threat source						
Chain	Factor-forming	Direct	Secondary			
Criteria for assessing the ways of spreading the threat impact						
1. Factor for assessing the scale of the threat spread						
Global	Interstate	Regional	Includes objects of the nature protection fund	Localized	Local	
2. Factor for assessing the environment of threat spread						
Atmospheric air	Groundwater	Surface water	Soil	Seawater		
3. Factor for assessing the mode of operation of the threat source						
Constantly acting	Periodically acting	Episodic acting	One-time	Random		
4. Factor for assessing the mobility of the threat						
Moving	Slowly moving	Immobile				
Criterion for assessing the recipients of the threat impact						
1. Factor for assessing the level of threat impact						
Landscape	Ecosystem	Floristic	Faunistic	Population	Species	
2. Factor for assessing the depth of threat impact						
Irreversible	Partially reversible	Reversible				
3. Factor for assessing the intensity of threat impact						
High	Medium	Low				
Integral threat assessment criterion						

Each partial criterion J_i consists of a set of factors f_{ji}. To obtain expert assessments of the relevant impacts of threats, experts fill out questionnaires in which they assign appropriate scores to the characteristics of factors e_i, the values of which can be recorded in an evaluation scale or a scale corresponding to the MAI evaluation scale [10, 11]. The evaluation scale lies between ordinal and interval types. The processing of evaluation scores is carried out as follows: if there is confidence that all experts use a single evaluation scale (understand the "evaluation value" in the same way), as is the case, for example, in the presence of exceptional standards, then the evaluation scale approaches the interval scale, and the evaluation scores are processed as quantitative (and the evaluation scale itself has a large number of gradations).

Research results and their discussion. The analysis method of hierarchies (developed by the American mathematician Thomas Saaty in the early 1990s) is a method of systematic analytical research and solving multicriteria problems, which can be systematically hierarchically structured through step-by-step decomposition. The essence of which, as set out with the adaptation of the publication [12], is as follows:

1. Determination of the goal (focus) of the problem.
2. System analysis and structuring of the problem in a hierarchical model (goal, criteria, factors, characteristic indicators, alternative solutions).
3. A database of factors, conditions, characteristics, indicators, and alternatives is formed through expert-analytical systems research.
4. Formulate a block of questions for comparing elements of all levels of the hierarchy and identifying hierarchical relationships of subordination and dependence, surveying experts, and filling in matrices of pairwise comparisons of aspects of each level by a group of experts, which includes a system analyst.
5. Determination of eigenvectors of pairwise comparison matrices and their normalization. Assessment of the consistency of expert judgments based on the Consistency Ratio (CR). Verification of the consistency of comparison matrices. If necessary, clarification of experts' opinions should be provided through repeated analysis.
6. Determination of each hierarchy element's local and global priorities (weight coefficients).

Pairwise comparisons are made to determine the relative importance of elements. These comparisons are then expressed in integers on the Saati scale (Table 2). The same method and one evaluation scale should be given to unify the experts' responses. Experts fill in the matrices of pairwise comparisons of polygons for the corresponding criteria factors (Fig. 1).

When conducting pairwise comparisons, comparing an element with itself gives a unit; the result of comparing the first element with the second is the score a_{12}, the result of comparing the first element with the third is the score a_{13}, etc. Thus, each expert, independently of the others, conducts an examination, the results of which are recorded in a table representing the structure of the pairwise comparison matrices. At stage (3), $n(n-1)/2$ judgments are required to obtain each matrix [9].

2. Scale of evaluations of relative importance

Score	Definition	Explanation
1	Elements are equally important (priority)	Equal contribution of the two aspects to achieving the goal
3	Slight advantage of one over the other	Some conditions give a slight advantage to one over the other
5	Substantial advantage	There are strong facts that one is significantly more important than the other
7	Clear advantage of one over the other	There are undeniable facts about the advantages of one over the other
9	Extreme advantage	The obvious advantage of one over the other is beyond doubt
2, 4, 6, 8	Intermediate result of a decision between two neighboring considerations	Applied in a compromise case
Inverse sizes of the above numbers	If, when comparing one element with another, one of the above numbers is obtained (for example, 3), then when comparing the elements in reverse, we will get the inverse number (i.e., 1/3)	

The data of such assessments, obtained from m experts, are summarized in one general table or matrix of comparisons (Table 3) by the corresponding criterion, in each cell of which ij the number $\overline{a_{ij}}$, which is equal to the average sum of the scores of the advantage of the i-th polygon over the j-th by the corresponding criterion, obtained from all m experts:

$$\overline{a_{ij}} = \frac{1}{m} \cdot \sum_{k=1}^{m} a_{ij_k} , \quad (3)$$

where $k = \in \{1, 2, \ldots, m\}$, and m is the number of experts.

For each matrix of comparisons A, there is a solution to the equation

$$A \cdot w = \lambda_{\max} \cdot w, \quad (4)$$

where $\lambda_{\max}$ is the maximum eigenvalue.

3. Matrix of pairwise comparisons of the impact by criteria from the averaged ratings of all experts

Impact	x_1	…	x_i	…	x_n
x_1	$\overline{a_{11}} = 1$	…	$\overline{a_{1i}}$	…	$\overline{a_{1n}}$
…	…	…	…	…	…
x_i	$\overline{a_{i1}}$	…	$\overline{a_{ii}} = 1$	…	$\overline{a_{in}}$
…	…	…	…	…	…
x_n	$\overline{a_{n1}}$	…	$\overline{a_{ni}}$	…	$\overline{a_{nn}} = 1$

For each row of the matrix of comparisons of estimates averaged over "experts", the components of the eigenvector are sequentially calculated concerning the rows of the matrix:

$$w_1 = \left(\overline{a_{11}} \cdot \overline{a_{12}} \cdot \overline{a_{13}} \cdot \ldots \cdot \overline{a_{1n}}\right)^{1/n},$$
$$w_1 = \left(\overline{a_{21}} \cdot \overline{a_{22}} \cdot \overline{a_{23}} \cdot \ldots \cdot \overline{a_{2n}}\right)^{1/n}, \quad (5)$$
$$w_1 = \left(\overline{a_{31}} \cdot \overline{a_{32}} \cdot \overline{a_{33}} \cdot \ldots \cdot \overline{a_{nn}}\right)^{1/n},$$

which are normalized by division by $\sum_{i=1}^{n} w_i$ and allow us to determine the weighting factors:

$$k_i = \frac{w_i}{\sum_{i=1}^{n} w_i} . \quad (6)$$

After normalization, the resulting vector w gives the importance or priority coefficients that show the contribution of each element to achieving the corresponding goal. These eigenvector components concerning the rows of the comparison matrix are also used to assess the consistency of the experts' assessments.

After all pairwise comparisons are conducted, the Consistency Index (*CI*) and the *CR* are determined. The *CI*, which provides information about violating the numerical and transitive matrix of comparisons, is an essential element of this model for determining the weight coefficients of the compared impact. Therefore, this index can indicate the "degree of consistency", i.e., the errors in the ratios $a_{ik} = a_{ij} \cdot a_{jk}$, $k = \overline{1,n}$, $i = \overline{1,n}$, and $j = \overline{1,n}$.

The following formula holds for *CI* [159]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} , \quad (7)$$

where n is the number of elements to be compared. For an inversely symmetric matrix, always

$$\lambda_{\max} \geq n . \quad (8)$$

Next, the *CI* obtained is compared with the value resulting from a random selection of numerical comparisons from the scale 1/9, 1/8, …, 1, 2, …, 9, forming a reciprocal (inverse symmetric) matrix.

If the *CI* is divided by the number corresponding to the average random consistency (*RI*) of a matrix of the same order, the result is the *CR*:

$$RI = \frac{CI}{CR} . \quad (9)$$

Table 4 shows the average consistency for different orders' random (probability) matrices.

The *CR* should be on the order of 10 % or less to be acceptable. In some cases, 20 % can be assumed, but not more. If the *CR* exceeds these limits, experts need to review the problem from the start and check their reasoning about the weighting factors.

After checking the *CR*, proceeding with the synthesis of priorities is necessary. Priorities are synthesized starting from the second level and moving downward. Local priorities are multiplied by the priority of the corresponding element at the higher level and summed for each component according to the importance or priority coefficients of each element it influences at every level of the hierarchy [9].

4. Average random consistency values for random inversely symmetric matrices of different orders

Matrix size	3	4	5	6	7	8	9	10	11	12	13	14	15
Average Random Consistency	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49	1,51	1,48	1,56	1,57	1,59

The priority vector of the WB $P_{vp} = \left\{P_{vp1}, \ldots, P_{vpn}\right\}$, consisting of components $P_{vpij}\left(i = \overline{1,n},\ j = \overline{1,3}\right)$, is an integral assessment of the corresponding i-th WB by the respective j-th criterion. For example, for the first WB:

$$\begin{aligned} &P_{vp11} = k_1 \cdot \overline{a_{11}} + k_2 \cdot \overline{a_{12}} + k_3 \cdot \overline{a_{13}}, \\ &P_{vp12} = k_1 \cdot \overline{a_{21}} + k_2 \cdot \overline{a_{22}} + k_3 \cdot \overline{a_{23}}, \\ &\ldots \\ &P_{vp1n} = k_1 \cdot \overline{a_{n1}} + k_2 \cdot \overline{a_{n2}} + k_3 \cdot \overline{a_{n3}}. \end{aligned} \tag{10}$$

Based on the calculated priority vector P_{vpij}, it is possible to rank the WB according to the selected evaluation criterion and compile the priority matrix:

$$\begin{pmatrix} & 1 & 2 & 3 & \ldots & L \\ x_1 & P_{vp_{11}} & P_{vp_{12}} & P_{vp_{13}} & \ldots & P_{vp_{1L}} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ x_i & P_{vp_{i1}} & P_{vp_{i2}} & P_{vp_{i3}} & \ldots & P_{vp_{iL}} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ x_n & P_{vp_{n1}} & P_{vp_{n2}} & P_{vp_{n3}} & \ldots & P_{vp_{nL}} \end{pmatrix}. \tag{11}$$

To compare the polygons $VP_1, \ldots, VP_n$ with each other based on vector criteria (see Fig. 1 and Table 1), formulas (3), (5), (6), (10), and (11) are used to obtain the components of the eigenvector concerning the rows of the priority matrix:

$$W_i^* = \sqrt[L]{P_{vpi1} \cdot \ldots \cdot P_{vpiL}}\ , \tag{12}$$

These are normalized by dividing by the $\sum_{i=1}^{n} W_i^*$ and used to determine the weighting coefficients:

$$\overline{W_i^*} = \frac{W_i^*}{\sum_{i=1}^{n} W_i^*}, \tag{13}$$

with these, the integral evaluations of the corresponding i-th WB can be obtained (formula 1).

Stages (3), (4), and (5) are carried out for all levels and groups within the hierarchy.

Next, hierarchical synthesis is applied to weight the eigenvectors by the importance or priority coefficients of the criteria, and the total sums are calculated for all relevant weighted components of the eigenvectors at each lower level of the hierarchy.

$$\begin{array}{l|l} VP_1 & VP_1 = \overline{W_1^*} \cdot P_{vp_{11}} + \overline{W_2^*} \cdot P_{vp_{12}} + \overline{W_3^*} \cdot P_{vp_{13}} + \ldots + \overline{W_L^*} \cdot P_{vp_{1L}}, \\ VP_2 & VP_2 = \overline{W_1^*} \cdot P_{vp_{21}} + \overline{W_2^*} \cdot P_{vp_{22}} + \overline{W_3^*} \cdot P_{vp_{23}} + \ldots + \overline{W_L^*} \cdot P_{vp_{2L}}, \\ \ldots & \ldots \\ VP_n & VP_n = \overline{W_1^*} \cdot P_{vp_{n1}} + \overline{W_2^*} \cdot P_{vp_{n2}} + \overline{W_3^*} \cdot P_{vp_{n3}} + \ldots + \overline{W_L^*} \cdot P_{vp_{nL}}. \end{array} \tag{14}$$

The consistency of the entire hierarchy is found by multiplying each *CI* by the priority or importance coefficient of the respective criterion and summing the resulting values. The result is then divided by a similar expression using the *RI*, corresponding to each priority-weighted matrix's dimensions (Table 3). Notably, the acceptable *CR* should be around 10 % or less. Otherwise, the quality of judgments should be improved by reviewing the method of formulating pairwise comparison questions. If this does not help, the task should be restructured more precisely by grouping similar elements under more significant criteria. Returning to stage (2) is necessary, even if only the uncertain parts of the hierarchy require revision [9].

Then, based on the initial assumption that differences in expert responses are explained by random independent fluctuations around some "true" values, conventional statistical methods of point estimation can be applied to process the evaluation data. Each WB is assigned an average score:

$$x_j = \tfrac{1}{m} \cdot \sum_{i=1}^{m} x_{ij},\ \ j = 1, 2, ..., n\,. \tag{15}$$

These evaluations (15) are considered group assessments. During the comprehensive evaluation procedure, the values of threat indicators and indices are projected onto the corresponding scale values.

The arguments of the target function e_i, which represent the factor indicators in the threat evaluations for the respective criteria components, are expressed in dimensionless scores. To evaluate the factors within partial criteria, three systems of equations are developed:

1. Criterion for assessing the source of the threat:

$$\begin{cases} f_{11}(e^1) = 0,29 \cdot {e^1}_{11} + 0,24 \cdot {e^1}_{12} + 0,19 \cdot {e^1}_{13} + \\ +0,14 \cdot {e^1}_{14} + 0,09 \cdot {e^1}_{15} + 0,05 \cdot {e^1}_{16}, \\ f_{12}(e^1) = 0,2 \cdot {e^1}_{21} + 0,18 \cdot {e^1}_{22} + 0,16 \cdot {e^1}_{23} + \\ +0,13 \cdot {e^1}_{24} + 0,11 \cdot {e^1}_{25} + 0,09 \cdot {e^1}_{26} + \\ 0,07 \cdot {e^1}_{27} + 0,04 \cdot {e^1}_{28} + 0,02 \cdot {e^1}_{29}, \\ f_{13}(e^1) = 0,29 \cdot {e^1}_{31} + 0,24 \cdot {e^1}_{32} + 0,19 \cdot {e^1}_{33} + \\ +0,14 \cdot {e^1}_{34} + 0,09 \cdot {e^1}_{35} + 0,05 \cdot {e^1}_{36}, \\ f_{14}(e^1) = 0,4 \cdot {e^1}_{41} + 0,3 \cdot {e^1}_{42} + 0,2 \cdot {e^1}_{43} + 0,1 \cdot {e^1}_{44}; \end{cases} \qquad (16)$$

2. Criterion for determining the pathways of threat impact distribution:

$$\begin{cases} f_{21}(e^2) = 0,29 \cdot {e^2}_{11} + 0,24 \cdot {e^2}_{12} + 0,19 \cdot {e^2}_{13} + \\ +0,14 \cdot {e^2}_{14} + 0,09 \cdot {e^2}_{15} + 0,05 \cdot {e^2}_{16}, \\ f_{22}(e^2) = 0,33 \cdot {e^2}_{21} + 0,27 \cdot {e^2}_{22} + 0,2 \cdot {e^2}_{23} + \\ +0,13 \cdot {e^2}_{24} + 0,07 \cdot {e^2}_{25}, \\ f_{23}(e^2) = 0,33 \cdot {e^2}_{31} + 0,27 \cdot {e^2}_{32} + 0,2 \cdot {e^2}_{33} + \\ +0,13 \cdot {e^2}_{34} + 0,07 \cdot {e^2}_{35}, \\ f_{24}(e^2) = 0,5 \cdot {e^2}_{41} + 0,33 \cdot {e^2}_{42} + 0,17 \cdot {e^2}_{33}; \end{cases} \qquad (17)$$

3. Criterion for assessing the recipients of the impact from the threat source:

$$\begin{cases} f_{31}(e^3) = 0,29 \cdot {e^3}_{11} + 0,24 \cdot {e^3}_{12} + 0,19 \cdot {e^3}_{13} + \\ +0,14 \cdot {e^3}_{14} + 0,09 \cdot {e^3}_{15} + \\ +0,05 \cdot {e^3}_{16}, \\ f_{32}(e^3) = 0,5 \cdot {e^3}_{21} + 0,33 \cdot {e^3}_{22} + 0,17 \cdot {e^3}_{23}, \\ f_{33}(e^3) = 0,5 \cdot {e^3}_{31} + 0,33 \cdot {e^3}_{32} + 0,17 \cdot {e^3}_{33}. \end{cases} \qquad (18)$$

After evaluating the factors, the values of the partial criteria are calculated. If an additive target function is used, the partial criteria are computed using the following formulas:

1. Criterion for assessing the source of the threat:

$$J_1(e^1) = 0,47 \cdot f_{11}\left(e^1\right) + 0,28 \cdot f_{12}\left(e^1\right) + \\ +0,16 \cdot f_{13}\left(e^1\right) + 0,09 \cdot f_{14}\left(e^1\right), \qquad (19)$$

2. Criterion for determining the pathways of threat impact distribution:

$$J_2(e^2) = 0,51 \cdot f_{21}\left(e^2\right) + 0,26 \cdot f_{22}\left(e^2\right) + \\ +0,14 \cdot f_{23}\left(e^2\right) + 0,09 \cdot f_{24}\left(e^2\right), \qquad (20)$$

3. Criterion for assessing the recipients of the impact from the threat source:

$$J_3(e^3) = 0,67 \cdot f_{31}\left(e^3\right) + 0,2 \cdot f_{32}\left(e^3\right) + \\ +0,13 \cdot f_{33}\left(e^3\right), \qquad (21)$$

4. Integral criterion for threat assessment:

$$J_\Sigma(e) = 0,65 \cdot J_1(e^1) + 0,23 \cdot J_2(e^2) + \\ +0,12 \cdot J_3(e^3). \qquad (22)$$

Thus, with this approach, the task of identifying WB's environmental safety level is reduced to comparing the obtained score assessments and ranking them based on a set of partial or integral criteria.

According to the theory of the AHP, it is necessary to form the essential and sufficient elements at each level of the generalized factors for analyzing the environmental safety status of WB (Fig. 2). The hierarchical scheme

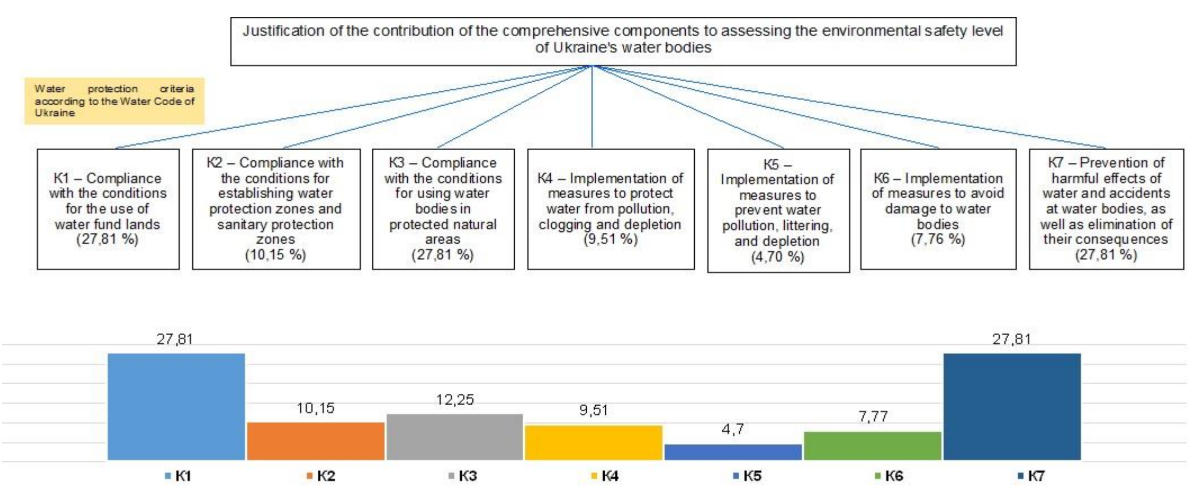


Fig. 2. Weighted contribution of each of the complex component criteria K in assessing the level of ecological safety of water bodies in Ukraine

titled "Justification of the Contribution of Comprehensive Assessment Components to the Level of Environmental Safety of Water Bodies in Ukraine" was developed based on expert ecological-analytical evaluation using the AHP method by T. Saaty [5].

The overall consistency score of the hierarchy is 0.02903, which meets the conditions for valid application of AHP. The generalized weight coefficients of the contributions of each element were obtained using computer software that implements the method.

Determining the environmental safety of WB, in the context of the requirements of the Water Code of Ukraine (in particular, Section Four on water protection), is logically structured using integrated criteria K1 to K7.

The criteria cover all critical aspects of the evaluation objective, while striving to minimize their number: K1 – Compliance with the conditions for the use of water fund lands; K2 – Compliance with the conditions for establishing water protection zones and sanitary protection zones; K3 – Compliance with the conditions for using WB in protected natural areas; K4 – Implementation of measures to prevent water pollution, littering, and depletion; K5 – Compliance with conditions for the placement of enterprises and related requirements; K6 – Implementation of measures to avoid damage to WB; K7 – Prevention of harmful effects of water and accidents at WB, as well as elimination of their consequences.

Each criterion from K1 to K7 jointly forms a generalized integral (emergent) contribution toward achieving the defined goal and reflects the full range of scientific and applied regulatory requirements established in the legal framework of Ukraine. The use of the AHP allows for expert-analytical determination of the contribution of each of these elements to the prioritization of the stated comprehensive objective.

The AHP methodology requires the formulation of verbal question blocks addressed to expert analysts for pairwise comparison of elements at each level. These comparisons evaluate each criterion's dominance, priority, and relative contribution compared to others using the specific Saaty scale.

The questions are formulated for the level of elements K1 to K7: *"Which criteria K is more important, essential, or desirable, compared to each of K1 to K7, in achieving the hierarchical goal?"*. After conducting pairwise comparisons, the assessment and *CI* of expert opinions are determined. These must align with the matrix dimensions or number of elements being compared, which are mathematically justified and experimentally confirmed by T. Saaty [5]. This requirement is one of the fundamental ideological premises for applying AHP correctly.

The criteria for sources of natural and anthropogenic formation of the current state of WB include the following: FIP1 – Impacts of processes in the abiotic environment of WB; FIP2 – Impacts of processes in the biotic environment of WB; FIP3 – Impacts of processes associated with anthropogenic (technogenic) pressure of WB (Fig. 3).

For the FIP1–FIP3 criteria level, the questions are formulated as: *"How is the influence of element FIP more important, more probable, more significant, etc., compared to each of the elements FIP1 to FIP3 as sources of natural and anthropogenic formation of the state of WB, within the aspects of compliance with*

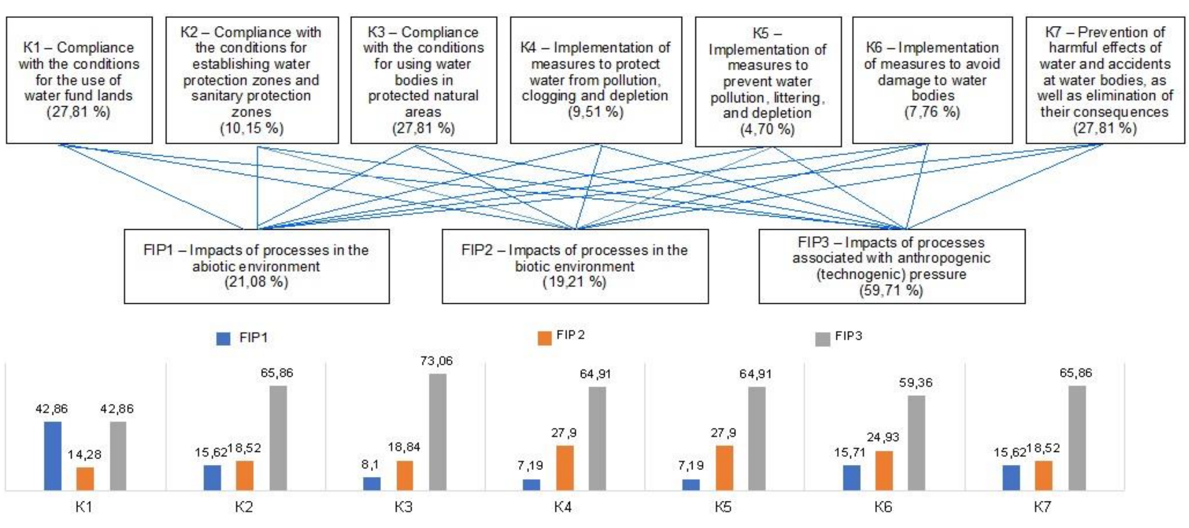


Fig. 3. Weight contribution of each of the elements of the FIP level in each criterion of the K level

each criterion of the higher level K1 to K7?”. Which, in turn, as characteristic parameters of the predicted impact on a WB in the aspects of each element of the higher level FIP1, …, FIP3 can be generally described as sources of impact, taking into account all the necessary elements with characteristic parameters of the predicted impact on WB CP1, …, CP4. The following are taken as characteristic parameters of the predicted impact on WB: CP1 – Quantitative characteristics of the predicted impact; CP2 – Qualitative characteristics of the expected impact; CP3 – Conditions for the accumulation of risks of the impact hazard; CP4 – The possibility of regulating the safety of the impact (Fig. 4) [9].

For the CP1–CP4 level, the evaluation questions are posed as: *“How does the assessed criterion CP dominate the identified FIP processes, and to what extent is it more significant, more probable, more influential, etc., in comparison with each of the listed CP1 to CP4 elements?”.* The most difficult to systematize is to substantiate the necessary and sufficient elements to summarize all the negative impacts on the environment that should be selected as the resulting types of consequences of natural and anthropogenic loading (NAP1, …, NAP7), which are already enshrined in regulatory legal acts on environmental safety, in particular in references to the Water Code of Ukraine, and have been studied by scientists before, are being studied now and will be studied in the future to assess and minimize such impacts effectively. The following negative consequences of natural and anthropogenic loading on WB are defined in the general structural and logical scheme: NAP1 – Landscape change (dams, canals, reservoirs, ponds, etc.); NAP2 – Destruction of soil cover (beams, washouts, mudflows, etc.); NAP3 – Deformation of the Earth’s crust layers (landslides, sinkholes, etc.); NAP4 – Chemical pollution of territories and WB; NAP5 – Violation of the water regime of territories (drainage, flooding, waterlogging, desertification); NAP6 – Risk of increased morbidity among the population; NAP7 – Loss of biodiversity of territories and WB (Fig. 5).

For the criteria level NAP1 to NAP7, evaluation questions are posed as follows: *“How do the identified processes associated with the evaluated NAP element dominate, and to what extent are they more significant, more probable, more impactful, etc., compared to each of the NAP1 to NAP7 elements, in the context of each of the higher-level criteria CP1 to CP4?”.*

The final level of the systematic hierarchical approach to achieving water safety in terms of environmental security of the state is divided into four directions of generalized assessment components (GC), designated as GC1 to GC4: GC1 – Justification of the environmental status of water safety components; GC2 – Justification of the level of anthropogenic pressure and its influence on WB; GC3 – Justification of the composition of typical pollutants in WB; GC4 – Justification of the level of background pollution in WB (Fig. 6).

For the lowest level elements GC1 to GC4, the comparative evaluation questions are formulated as: *“What is the contribution and priority of each GC element in pairwise*

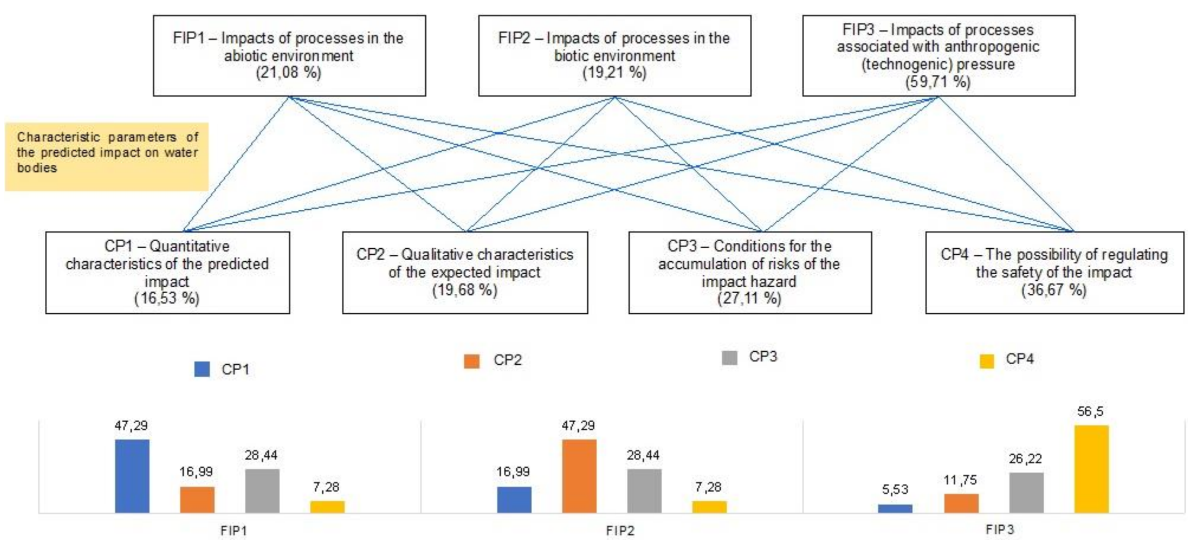


Fig. 4. Weight contribution of each of the elements of the CP level in each of the criteria of the FIP-level

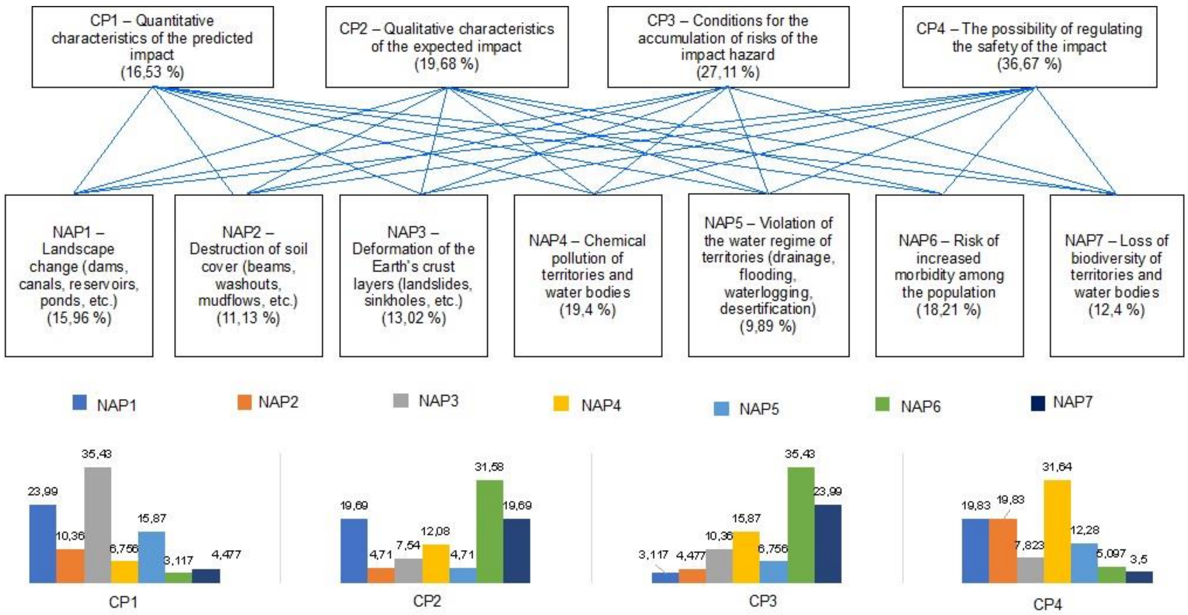


Fig. 5. Weight contribution of each of the elements of the CP level in each criterion of the FIP level

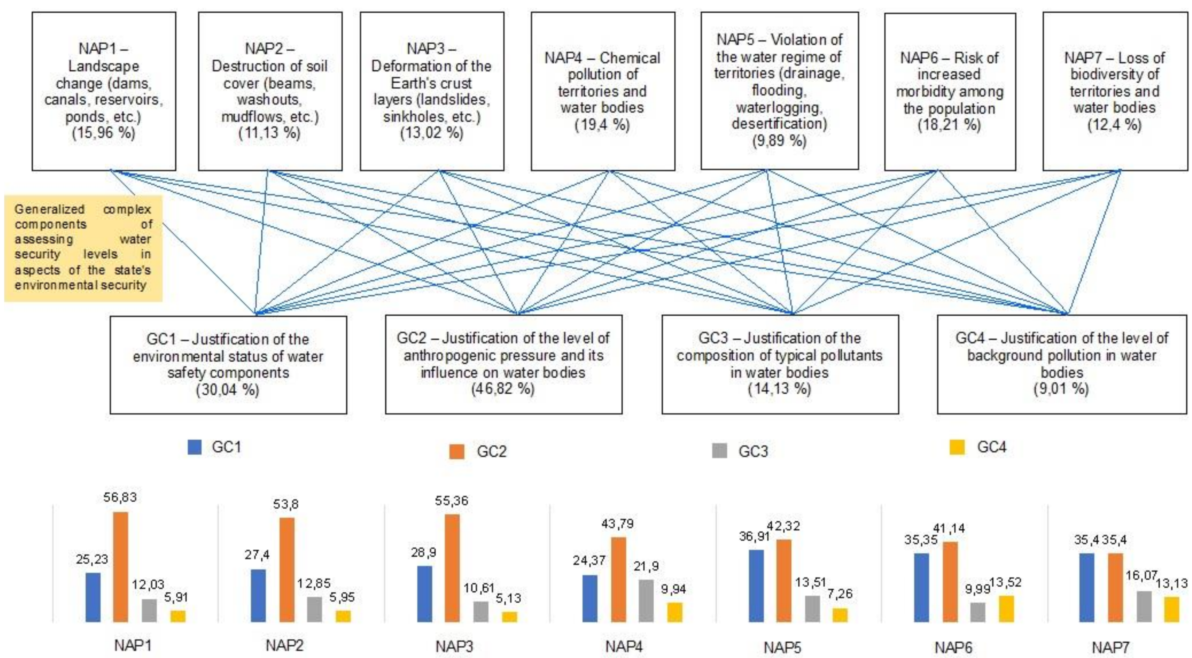


Fig. 6. Weight contribution of each of the elements of the GC level in each criterion of the NAP level

comparison with the other GC1 to GC4 elements, in evaluating the influence of each of the previously defined criteria NAP1 to NAP7, which describe the negative consequences of natural and anthropogenic pressure on the state's WB?". The objectivity of solving the task of identifying the environmental safety level of WB is conditioned by the requirements of the Water Code of Ukraine on water protection and by the adequacy of the criteria in covering the whole chain of evaluation factors and their characteristics [9].

In the developed structural and logical model shown in Figure 7, pairwise comparisons are conducted regarding the dominance of one element over another. These comparisons are then expressed in integers according to the Saaty scale (Table 2). Standard statistical point estimation methods can be applied to process the evaluation data based on the assumption that differences in expert responses are caused by random, independent fluctuations around specific "true" values.

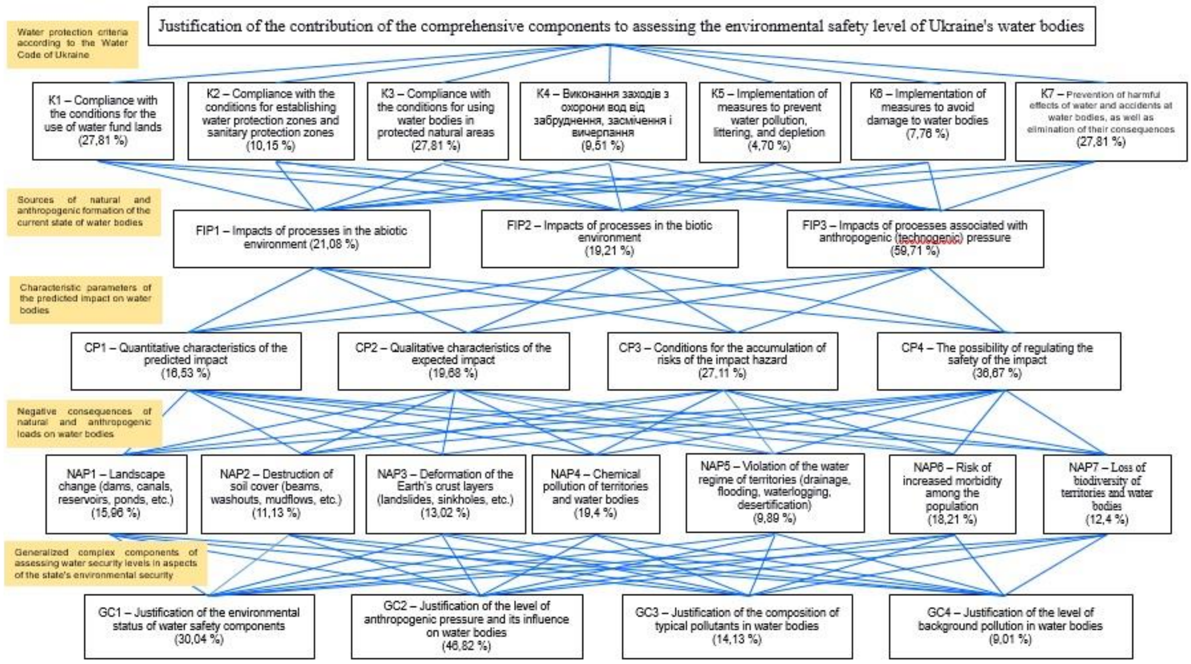


Fig. 7. Hierarchical structural and logical scheme for identifying the level of ecological safety of water bodies

During the identification procedure, the values of indicators and indices of the respective characteristics are projected onto corresponding scales. The arguments of the identification objective function e_i, which represent the features of evaluation factors according to the relevant components of the criteria, are expressed as dimensionless score values.

Thus, the task of identifying WB's environmental safety level is reduced to comparing the obtained score-based assessments and ranking them according to a set of partial or integral criteria (index).

The definition of a set of environmental protection measures without analyzing the rationality of economic use of the catchment area of watercourses based on the assessment of the impact of negative factors that accelerate degradation processes, and positive factors that may lead to stabilization and improvement of the ecological status of river basins is costly and inefficient. Selecting the most effective and economically feasible environmental protection measures is necessary to reduce the intensity of degradation processes in small river basins. The water-protection effectiveness of these measures is evaluated based on: the level of protection from dissolved and sorbed agrochemicals; the duration and rate of manifestation of the protective effect; their universality and the number of additional effects (e.g., increased agricultural productivity, additional yields due to increased moisture reserves, prevention of water erosion, gully formation, and bank abrasion, reclamation of low-productivity lands, reduction of reservoir siltation, increase in base river flow, and improvement of meadow-forest landscapes and microclimate conditions); and the economic costs of implementing each environmental protection measure [13].

It is important to note that researchers studying the protection of water resources during armed conflicts have emphasized that, despite international legal norms for protecting WB during armed conflicts, such norms have failed to safeguard this critically important resource [13] adequately. As demonstrated by the war in Ukraine and other military conflicts [14], international legal norms for protecting WB under such conditions are neither functional nor practical.

Conclusions. A method for identifying the level of ecological safety of WB under conditions of uncertainty has been developed, which is solved by methods of system analysis using a multicriteria approach. With this approach, identifying WB's environmental safety level is reduced to comparing the obtained score estimates and ranking them by a set of partial or integral criteria (index).

Using the hierarchy analysis method to substantiate the contribution of complex components in assessing the ecological safety of WB in Ukraine is a key element that allowed the best solution to be chosen for applying the assessment methodology. First of all, it is based on the terms: "usefulness", "limitations", "opportunities" and "risks", which are first assessed separately as components of the requirements of the Water Code of Ukraine, and then, through a comparative assessment, are combined on a single scale and synthesized into an analytical solution, where each element has its priority and weight, and in general – combines a single holistic approach to achieve a specific result, namely the ecological safety of WB – where the first of the management measures is a substantiated scientific assessment.

References

1. Saaty, T. L. (1982). Decision making for leaders: The analytical hierarchy process for decisions in a complex world. Lifetime Learning Publications.

2. Ming, D., Yaxin, S., & Guiqiu, L. (2019). Optimized urban water security regulation schemes driven by industrial development pattern. *Water Policy*, 21 (3), 676–691. DOI: https://doi.org/10.2166/wp.2019.198

3. Gerlak, A. K., House-Peters, L., Varady, R. G., Albrecht, T., Zúñiga-Terán, A., de Grenade, R. R., & Scott, C. A. (2018). Water security: A review of place-based research. *Environmental Science & Policy*, 82, 79–89. DOI: https://doi.org/10.1016/j.envsci.2018.01.009

4. Linstone, H. A., & Turoff, M. (Eds.). (1975). The Delphi method: Techniques and applications. Reading, MA: Addison-Wesley.

5. Saaty, T.L. (2009). Mathematical principles of decision making (Principia Mathematica Decernendi). Pittsburgh, PA: RWS Publications. ISBN 1-888603-10-0

6. Bondar, O.I., Tarariko, O.G., & Varlamov, E.M. (2006). Vprovadzhennia yevropeiskykh standartiv i normatyviv u derzhavnu systemu monitorynhu dovkillia Ukrainy [Implementation of European standards and norms in the State Environmental Monitoring System of Ukraine]. Kyiv: Inres [in Ukrainian].

7. Cabinet of Ministers of Ukraine. (2018, September 19). Postanova Pro zatverdzhennia Poriadku zdiisnennia derzhavnoho monitorynhu vod № 758 [Resolution on the Procedure for State Water Monitoring, No. 758]. *Uriadovyi Kurier*, № 185. Retrieved from: https://zakon.rada.gov.ua/laws/show/758-2018-%D0%BF#Text [in Ukrainian]

8. Chumachenko, S. M., Dudkin, O. V., Korzhnev, M. M., & Yakovlev, E. O. (2003). Metodychni aspekty otsinky i ranzhuvannia zahroz dlia bioriznomanittia v Ukraini [Methodological aspects of assessing and ranking threats to biodiversity in Ukraine]. *Ekolohiya i resursy, Zb. nauk. prats. UINSiR RNBOU*, 7, 77–86 [in Ukrainian].

9. Yatsiuk, M. V. (2025). Rozvytok naukovykh zasad otsiniuvannia vodnoi bezpeky Ukrainy yak skladovoi ekolohichnoi bezpeky [Development of scientific foundations for assessing water security of Ukraine as a component of environmental security] (Doctoral dissertation). Kyiv. [in Ukrainian]

10. Jensen, O., & Wu, H. (2018). Urban water security indicators: Development and pilot. Environmental Science & Policy, 83, 33–45. https://doi.org/10.1016/j.envsci.2018.02.003

11. Ginkel, K. C. H., Hoekstra, A. Y., Buurman, J., & Hogeboom, R. J. (2018). Urban water security dashboard: Systems approach to characterizing the water security of cities. *Journal of Water Resources Planning and Management*, 144 (12), 04018072. DOI: https://doi.org/10.1061/(ASCE)WR.1943-5452.0000997

12. Lisichenko, H. V., Khmil, H. A., & Barbashev, S. V. (2011). Metodolohiia otsiniuvannia ekolohichnykh ryzykiv [Methodology for environmental risk assessment]. Odesa: Astroprynt. [in Ukrainian].

13. Rybalova, O. V. (2011). Kompleksnyi pidkhid do vyznachennia ekolohichnoho stanu baseiniv malykh richok [An integrated approach to determining the ecological status of small river basins]. *Problemy okhorony navkolyshnoho pryrodnoho seredovyshcha ta tekhnohennoi bezpeky, Zbirnyk naukovykh prats UkrNDIEP*, (33), 88–97. [in Ukrainian]

14. Pashchenko, O. M., & Hoshtynar, S. L. (2022). Mizhnarodno-pravovi zasady harantuvannia vodnoi bezpeky pid chas voiennykh konfliktiv. [International legal principles for guaranteeing water safety during military conflicts]. ENVIRONMENTAL LAW, (3–4), 57–62. DOI: https://doi.org/10.37687/2413-7189.2022.3-4-4.12 [in Ukrainian].

УДК 332.142.6:504:556

МЕТОД ІДЕНТИФІКАЦІЇ РІВНЯ ЕКОЛОГІЧНОЇ БЕЗПЕКИ ВОДНИХ ОБ'ЄКТІВ

М.В. Яцюк[1], докт. техн. наук, С.М. Чумаченко[2], докт. техн. наук, О.О. Сидоренко[3], канд. с.-г. наук, О.В. Тураєва[4]

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-5535-715X, e-mail: mv_yatsiuk@ukr.net;
[2] Державний науково-дослідний інститут авіації Міноборони України, Київ;
https://orcid.org/0000-0002-8894-4262, e-mail: sergiy23.chumachenko@gmail.com;
[3] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-7377-6809, e-mail: 63059@ukr.net;
[4] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-3367-404X, e-mail: turaieva.olga@gmail.com

Анотація. *Розроблено метод ідентифікації рівня екологічної безпеки водних об'єктів в умовах невизначеності, що розв'язується методами системного аналізу з використанням багатокритеріального підходу. Вирішення задачі підвищення адекватності ідентифікації полягає не тільки в пошуку адекватнішого критерію, але й у використанні декількох критеріїв, що описують різносторонньо мету ідентифікації рівня екологічної безпеки водних об'єктів і доповнюють один одного. Визначення екологічної безпеки водних об'єктів в аспектах вимог Водного Кодексу України доцільно структурувати за комплексними критеріями. Метод ідентифікації рівня екологічної безпеки водних об'єктів використовує прийоми обчислення бальних оцінок різних факторів, що характеризують окремі складові конкретних критеріїв. Об'єктивність вирішення задачі ідентифікації рівня екологічної безпеки водних об'єктів обумовлюється забезпеченням критеріями достатньо повного ланцюга оцінювання ознак загроз. Процедура проведення ідентифікації базується на підходах багатокритеріальної оцінки з подальшою згорткою її до інтегрального індексу, який буде визначати рівень екологічної безпеки водного об'єкту. При проведенні процедури ідентифікації значення індикаторів і індексів відповідних характеристик проектуються на значення відповідних шкал. Аргументи цільової функції ідентифікації, які є ознаками чинників оцінювання за відповідними складовими критеріями, виражаються балами в безрозмірному вигляді. Задача ідентифікації рівня екологічної безпеки для природних чи техногенних об'єктів в умовах невизначеності розв'язується методами системного аналізу з використанням багатокритеріального підходу і зводиться до порівняння отриманих бальних оцінок і ранжування їх за сукупністю часткових критеріїв чи інтегральним критерієм (індексом). Використання методу аналізу ієрархії для обґрунтування вкладу комплексних складових оцінювання рівня екологічної безпеки водних об'єктів України є ключовим елементом, що дозволило вибрати найкраще рішення щодо застосування методології оцінювання.*

Ключові слова: *антропогенне навантаження, водні об'єкти, екологічна безпека, природно-технічні геосистеми*

DOI: https://doi.org/10.31073/mivg202501-418
Available at: https://mivg.iwpim.com.ua/index.php/mivg/article/view/418

UDC 631.4: 53.01

CONCEPT OF INVOLVING GASES IN THE FORMATION OF THERMODYNAMIC AVAILABILITY OF PLANT NUTRIENTS AND THE COURSE OF SOIL PROCESSES

S.S. Kolomiiets[1], Ph.D., M.I. Romashchenko[2], Dr. of Technical Sciences, A.S. Sardak[3], Ph.D.

[1] Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Kyiv, Ukraine; https://orcid.org/0000-0002-4329-4382; e-mail: kss2006@ukr.net;
[2] Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Kyiv, Ukraine; https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com;
[3] Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Kyiv, Ukraine; https://orcid.org/0000-0002-0540-9492; e-mail: anastasiabilobrova1993@gmail.com

"Soil without gases is not soil, soil chemistry cannot be known – even in its general features – by studying only the solid and liquid components of the soil"
V.I. Vernadsky [1]

Abstract. *The important role of gases in the planetary energy-mass exchange of the lithosphere with the atmosphere is determined, and attention is focused on the multifaceted mechanisms of gas exchange, especially under non-isothermal soil conditions. The conceptual principles of involving gases in ensuring the thermodynamic availability of plant nutrition, which emphasize the role of gases in a heterogeneous soil system, which is characterized by the presence of trapped air bubbles, are based on experimental data. Trapped soil air bubbles in the soil environment play the role of a distributed energy source when interacting with the thermodynamic parameters of the environment – temperature, atmospheric pressure and soil moisture content. The reaction of the soil capillary potential to a daily dynamics of external thermodynamic parameters has the nature of a self-oscillating process with a significant amplitude of the thermodynamic availability of the pore solution for plants.*

This turns the trapped air bubbles into centers of thermodynamic disequilibrium (CTD), acid centers of a certain strength (AC) and ecotone centers of soil biota. Thermodynamic accessibility is determined by the dynamics of soil heterogeneity, i.e. its energy saturation with surface types of energy, as well as by increasing matter mobility and intertransitions of different categories of soil absorption capacity. The functional parameters of the soil are determined by the gas composition of the soil atmosphere, where a special role belongs to carbon dioxide (CO_2), as the main factor in maintaining soil homeostasis. Emphasis is placed on the fact that under natural conditions of soil functioning, the composition of the smallest bubbles is enriched with oxygen and nitrogen, and most importantly, the size of these bubbles becomes close to nanoradii, which gives them abnormal properties.

Using the example of nanotechnologies with various gases, the possibility of targeted control of soil processes to increase the productivity and quality of plant products and ameliorative improvement of soils has been proven. The conclusion about the extremely high potential of integrating nanobubble technologies into ameliorative agriculture when using modern drip irrigation technologies has been made.

Keywords: *thermodynamic soil system, soil processes, soil gases, trapped air, nanobubbles, soil energetics, thermodynamic accessibility*

Relevance of the research. The Earth's epigeosphere is characterized by the transformation of huge flows of energy and matter, where a special role belongs to the pedosphere, as the lithospheric shell bordering the atmosphere, which actually regulates planetary energy and mass exchange with the environment and space. The patterns of pedosphere development are perhaps the most complex among all the Earth's geospheres. After all, all four phases interact and interpenetrate in it: solid matter – gases – moisture and living matter. Moreover, the role of living matter in the transformation of energy and mass exchange flows of the epigeosphere is constantly growing. V.I. Vernadsky drew attention to the biogenic structure of the modern atmosphere [2], which is changing its composition quite rapidly. And now significant anthropogenic emissions of greenhouse gases cause a greenhouse effect, which leads to global climate change towards warming and aridization [3].

Analysis of previous research and publications. The most significant evolutionary changes in properties occur in the pedosphere, as a regulator of the interaction of the lithosphere with the atmosphere, in which the decisive role belongs to atmospheric and soil gases. However, the role of these gases in the evolution of the pedosphere properties has not been fully studied yet. In recent years, the mechanism of emissions of greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), carbon monoxide (CO), hydrogen (H_2) and other minor atmospheric gases have been intensively studied [4]. However, the role of each gas in soil functioning and in living organisms lives has not been fully studied yet due to the extreme complexity of the heterogeneous soil system and the multifaceted functional purpose of gases.

It should be mentioned the imperfection of modern methods for studying the gas regime of soils [5]. And the current state of studying this problem is primarily due to the extreme complexity and multifaceted ways of moving gases in a heterogeneous four-phase environment of a highly organized soil system, which is also complicated by the cyclic non-isothermality of soil regimes. The most complete analysis of such mechanisms of cyclic migration of matter is considered in the theory of drying of various materials [6], where the mechanisms of moisture thermal diffusion, relative thermal diffusion of gases in a non-isothermal pore space, thermal sliding of gases, in the presence of a temperature gradient and many other specific mechanisms migration of substances in a heterogeneous environment are considered.

In particular, it has been proven [6] that due to the relative thermal diffusion of gases in soil pore space in the presence of a temperature gradient, water vapor with a molecular weight of $M_{H2O} = 18$ and carbon dioxide $M_{CO2} = 44$, compared to the average molecular weight of atmospheric air $M_{atm} = 29$, can move in opposite directions. Probably, one of such mechanisms is the enrichment of the soil atmosphere with CO_2 during non-isothermal evaporation of moisture from the soil. In mathematical models of gas migration, those prevail where the driving force of movement is the diffusion mechanism, i.e. movement along concentration gradients. However, such models are unsuitable for a heterogeneous soil environment.

Using the example of the thermal movement of moisture in the vapor state, it has been experimentally proven that the established actual flow of vaporous moisture in the soil, moving after the heat flow that occurs in the pore space of the soil due to the thermal sliding of gases [7], exceeds diffusion in intensity and can be provided only by the convective flow of soil air. Therefore, in the non-isothermal regime of the soil environment, the convective mechanism of gas movement in the pore space prevails.

The movement of water vapor under the influence of a temperature gradient generates circulatory (dissipative) structures where the capillary flow of moisture compensates for vaporous losses in certain areas of evaporation, which, in turn, causes a compensatory flow of liquid and convective transport of dissolved substances and change in their concentration in the zone of predominant moisture evaporation [7]. Such circulatory movements of moisture and gases in different phase states are typical for soil, which generally indicates the inconsistency of diffusion models of gas movement in soils and emphasizes the extreme complexity of mass transfer in the soil environment and its insufficient study.

The purpose of the publication is to form the conceptual principles of involving gases in ensuring the thermodynamic availability of plant nutrition from the soil and the transformation (dissipation) of energy in soil processes through the significant dynamics of heterogeneity, i.e. the variability of the surface area of the liquid-gas interface, as well as to substantiate the possibility of controlling the intensity of these processes by changing the gas composition of the soil atmosphere.

Materials and methods of research. The methodology of soil research, where soil is a non-equilibrium thermodynamic system, provides for the use of mainly thermodynamic hydrophysical field and laboratory research methods that are integrative for determining the parameters of the current thermodynamic state of a heterogeneous system of unsaturated soil. When using these methods [10], it was possible to differentiate the pore space of the soil by its fundamental property – hysteresis, i.e. the ambiguity of the relationship between capillary potential and soil moisture content.

Using the created "Method for determining the structure of soil pore space (dispersed media)" [8], it was possible to divide the total heterogeneity, i.e. the surface area of the liquid-gas interface, into extraheterogeneity (external), or the interface surface area when capillary moisture contacts with soil atmosphere, and intraheterogeneity (internal) – the contact area of the solution with the inner surface of trapped air bubbles. It is intraheterogeneity that turned out to be the most dynamic state parameter that ensures the dynamics of surface energy in unsaturated soil, i.e. its energy buffering: the storage of surface energy at the surface of the liquid-gas interface when air is trapped and its slow release as this area decreases due to the opening of the bubbles of intraheterogeneity. This phenomenon of hysteresis is used by soil biota and plants in their own production process to minimize their own energy consumption. The dynamic model of soil functioning and development in interaction with the environment [9], formulated using a systems approach, became the methodological basis for studying the role of gases in soils.

Research results and their discussion. Modern ideas about the gas regime of soils are imperfect. In particular, it is believed that the main mechanism of gas exchange is carried out by the processes of "soil respiration", where the processes of soil biota metabolism prevail. It has been already mentioned that there are other purely physical mechanisms of movement and selection of gases of the soil atmosphere [6, 7]. The dominance of purely agronomic views on "soil respiration" does not aim to consider the mechanisms of gas transformation and their role in the functional parameters of soil processes. And only considering the soil as a non-equilibrium thermodynamic system in interaction with the environment highlighted the extraordinary role of the gas component in the life of the soil and ensuring its productive function (fertility).

It has been experimentally established [10, 11] the emergence of subordinate (internal) energy-consuming processes of redistribution of matter with its phase transitions occurring in the soil, which transforms the soil environment into a microgradient structure with pulsating movements of energy and mass exchange in the environment of macropores with trapped air. These translational movements of a certain intensity (energy consumption) determine the level of soil homeostasis, which ensures the reproduction of the structural organization and basic properties of the soil environment [10], and it is the soil air bubbles, separated from the atmosphere by liquid membranes in the expansions of the pore space play the role of an energy source in the soil, responding to the variable cyclic external thermodynamic parameters – temperature, atmospheric pressure and moisture content.

For a better understanding of the dynamics of the trapped air content, a physical model of the soil pore space was created in the form of a corrugated equivalent capillary, which considers in detail the conditions for the existence of trapped air in the extensions of the soil pore space [11]. In particular, the condition for the equilibrium of a trapped air bubble is the equality of the curvature radii of the liquid membrane both from the outside, when it contacts with the atmosphere, and inside, which limits the inner surface of the trapped air $r_a = r_{зп}$. Such an equilibrium is possible in the range of pore sizes where де $r_{min} < r_{ta} < r_{max}$, where where r_{min} and r_{max} are the typical pore sizes determined by the sphere of the most inscribed radius in the pore body and r_{min} is the radius of the sphere inscribed in the necks of this pore.

The ratio of these typical pore sizes $n = \frac{r_{max}}{r_{min}}$ is an important characteristic that is determined in the laboratory diagnostics system by the amplitude of the capillary hysteresis loop [6, 11]. The threshold size of structural macroporosity is determined by the value $n > 2$ and the excess gas pressure that can be created in a bubble of trapped air $P_{надл} = 0{,}15\frac{r_{max} - r_{min}}{r_{max} \cdot r_{min}}$ depends on this ratio. That is, the greater this difference, the higher the excess pressure can be created in the bubble. That is why the largest structural soil macropores are very important in agronomy. In turn, under the action of excess pressure, the diffusion of gases that make up this bubble begins through liquid membranes to the soil atmosphere according to their solubility in the pore solution. Table 1 shows the comparative solubility of some gases.

Among the atmospheric gases, the solubility of oxygen (O_2) is 24,4 times lower compared to carbon dioxide (CO_2), and nitrogen is 46,6 times lower. Therefore, in bubbles of trapped air, when the excess preasure (P_{excess}) occurs, the gas composition is enriched in oxygen and nitrogen, according to their solubility in the pore solution.

The content of CO_2 in the soil atmosphere is increased, compared to the open atmosphere, approximately by 3 %, although in anaerobic

1. Solubility of some gases in water when T=25 °C, mol L^{-1} atm^{-1} [12]

Ammonia (NH_3)	Sulfur dioxide (SO_2)	Carbon dioxide (CO_2)	Methane (CH_4)	Oxygen (O_2)	Nitrogen (N_2)
57,0	1,25	0,0308	0,00129	0,00126	0,000661

conditions of some soils it can increase by 20 % or more. The main thing is that carbon dioxide dissociates in the pore solution forming carbonic acid H_2CO_3. Due to this, the bubbles of trapped air become acid centers of carbonic acid, forming a radial acidity gradient of the pore solution in the unsaturated soil and disrupting the carbonate equilibrium of the soil cement. It should be noted that carbon dioxide, in addition to the environmentally negative effect of its emission for the atmosphere, plays an extremely important role in soil functioning binding carbon and calcium in it, as well as ensuring the dynamics of thermodynamic availability of nutrients for plants from all categories of soil absorption capacity.

Soil energetics. Capturing soil air into the structure of the soil matrix and the including gases together with moisture into the components of the thermodynamic system of soil functioning as a working medium is of extremely importance in the conversion (dissipation) of the external solar energy flow, which generally determines soil energetics and its dynamics. An integral parameter of soil energy saturation is the thermodynamic moisture potential [9, 11]. The dynamics of soil capillary potential under the influence of the dynamics of variability of external thermodynamic parameters was experimentally investigated: temperature, atmospheric pressure and moisture content. In particular, a thermal pulse in the real range of daily temperature variability of an isolated soil sample at constant moisture content ($\theta = \text{const}$) causes a self-oscillating process of changing the capillary potential of the soil sampl. Initially, synchronously with heating, the capillary potential increases (decreases in absolute value), and with the onset of cooling it rapidly decreases to a minimum, and begins to slowly increase to the initial values [10]. Deviations of the capillary potential values in both directions from the initial values reach 20–40 kPa, and the total amplitude reaches 30–60 kPa, which is a fairly significant fluctuation in the thermodynamic availability of plant nutrition in the daily cycle.

The behavior of gases in the physical model of the pore space in the form of a corrugated equivalent capillary allow us to understand the processes of emerging the self-oscillating mode of the dynamics of the capillary potential [11]. With the onset of heating, the volume of trapped air in the soil expands, squeezing moisture out of the pore body. Having the effect of moistening this process leads to the closure of larger pores with liquid membranes and an increase in the values of the capillary potential. This is also facilitated by a decrease in the surface tension of the solution with increasing temperature. At the same time, the equilibrium conditions of the trapped air are disrupted in the smallest pores and it is compressed, increasing the intensity of the dissolution of gases in these bubbles, or small bubbles may be carried away by the convective flow of the pore solution to larger pores.

The increase in the capillary potential stops when these two opposite processes become equal in intensity. With the beginning of cooling, the minimum values of the current capillary potential are observed in the soil taking into account the dissolution of gases in the smallest pores, with the subsequent process of gas release from the pore solution. In this case, capillary meniscus forces cause tensile forces in the soil and slow restoration of the initial values of the capillary potential in the soil sample.

The saturation of the smallest bubbles of the trapped air with the least soluble oxygen (O_2), nitrogen (N_2) and their dissolution in the pore solution under excess pressure leads to the question – whether plants absorb them from the pore solution in the environment of the smallest pores? Perhaps this is one of the mechanisms of absorption of atmospheric nitrogen (N_2), which requires targeted further research. In particular, when having the values $P = -60$ kPa, the radius of the bubbles is $r \approx 2{,}5 \cdot 10^{-6}$, or 2500 nm, and when they are compressed, their size decreases by an order of magnitude. In this case, it is important that the smallest bubbles with a size of $1 \cdot 10^{-6} \div 1 \cdot 10^{-9}$, i.e. micro- and nano-radii, acquire anomalous properties.

The study of nanobubbles is a new aspect of science in the area of nanotechnology. In 1950, the Einstein-Plesset theory was proposed to predict the lifetime of bubbles, and in 1959, the American physicist Richard Feynman presented this concept, which demonstrated great potential for application in medicine, cosmetics, chemical technology, polymers, treatment and health care, and many other areas [13]. However, the rapid development of nanobubble technology began only in the third millennium. Nanobubbles with a size of $1 \cdot 10^{-6} \div 1 \cdot 10^{-9}$ м can occur naturally, in particular, the mechanism of nanobubbles in water on a hydrophobic surface is described [14].

There are plenty of such hydrophobic surfaces in soils, they are mainly films of organic substances on mineral particles. However, for industrial use, nanobubble generators have been invented that use different principles – cavitation, electrolysis, nanoporous membranes, ultrasound, and others. The importance of nanobubbles is based on their anomalous properties that distinguish them from other bubbles: they are electrochemically active, non-floating and non-toxic, stable and can remain in the aquatic environment for a rather long time, acquire a zeta potential, due to which they have the properties of colloids to involve ions into a double electric layer, and such involvement occurs on both surfaces of the bubble, which ensures the delivery of necessary elements to any organ in organisms.

Nanobubbles can be formed from various gases – oxygen, nitrogen, carbon dioxide, hydrogen, ozone and others, which have different effects on the purposefully controlled system. Among the multifaceted applications of nanobubble technologies, one should focus on their use in the agrosphere. There is already a lot of data on the positive impact of nanobubbles on yield, quality of grown products, water retention and other soil properties, in particular their structuring, mobilization of hard-to-reach biogens due to an increase in the number and selection of microbiota in the rhizosphere of plant roots, as well as other aspects of crop production [15–18]. The main element of the technology for using nanobubbles, mainly of oxygen (O_2) composition, was the technology of introducing nanobubbles into irrigation water supplied to plants by means of drip irrigation.

However, among the existing published data, the use of nanotechnologies in crop production has certain shortcomings, and most importantly, there is the lack of systematic application of nanobubble technologies. They show insufficient professionalism, experiments are conducted mainly in closed soil, and there is no interpretation of the effect of nanobubbles on the soil from the standpoint of soil science, agrophysics and land reclamation. In particular, it is observed an increase in soil moisture and water-holding soil capacity, but the impact of using nanotechnologies on the capillary soil properties is not yet considered, which may be of great importance for hydrotechnical land reclamation. Moreover, the impact of various gases on soils, which may become an element of land reclamation technologies in the future, is not considered either.

The study of using nanotechnologies in land reclamation agriculture is planned in the scientific program of the Institute of Water Problems and Land Reclamation in the next five-year period of 2026–2030.

Conclusions. The functioning of the soil as a thermodynamic system highlighted the extremely important role of the gas phase in the soil life, the transformation of energy and matter in it, which, ultimately, ensures its productivity.

An important role in these processes belongs to the bubbles of soil air trapped in the expansions of pores, as a form (mechanism) of involving gases into the heterogeneous soil environment. These bubbles become a source of thermodynamic disequilibrium (source of energy), acid centers and centers of ecotones of soil biota in the soil, which transform the soil into a microgradient dissipative structure with cyclic pulsating radial movements of energy and mass exchange with phase transitions of matter. Due to these processes, soil homeostasis is maintained and the reproduction of the basic properties and its structural organization is ensured.

Among the gases of the soil atmosphere, carbon dioxide (CO_2) plays an important role in soil functioning, so its content can be equated to one of the fertility parameters.

The technical capabilities of introducing gases with irrigation water by means of drip irrigation, including in the form of nanobubbles, will allow for more targeted control of soil regimes and their reclamation effect on the soil.

It is time to integrate nanobubble technologies into the practice of reclamation agriculture due to their extraordinary prospects in increasing the productivity and quality of plant products, improving the microbiological state of the soil and, perhaps most importantly, their environmental friendliness. The use of nanobubbles of various gas compositions will significantly expand the possibilities of reclamation technologies.

References

1. Vernadskyi, V.Y. (1960). K voprosu o khymycheskom sostave pochv [On the issue of the chemical composition of soils]. Yzbr. soch. T.V. Moskva, 325–327 [in russian].

2. Vernadskyi, V.Y. (1944). O znachenyy pochvennoi atmosferu y ee byohennoi strukturu [On the importance of the soil atmosphere and its biogenic structure]. *Pochvovedenye,* 4–5, 137–143 [in russian].

3. Romashchenko, M., Husyev, Y., Shatkovskyi, A., Saidak, R., Yatsyuk, M., Shevchenko, A., & Matiash, T. (2020). Vplyv suchasnykh klimatychnykh zmin na vodni resursy ta silskohospodarske vyrobnytstvo [Impact of climate change on water resources and agricultural production]. *Melioratsiia i vodne hospodarstvo*, 1, 5–22. DOI: https://doi.org/10.31073/mivg202001-235 [in Ukrainian].

4. Mynko, O.Y. (1988). Planetarnaia hazovaia funktsyia pochvennoho pokrova [Planetary gas function of soil cover]. *Pochvovedenye*, 7, 59–75 [in russian].

5. Metody yssledovanyia hazovoi funktsyy pochvy (1987). [Methods of studying the gas function of soil]. Sovremennыe fyzycheskye y khymycheskye metody yssledovanyia pochv: pod red. A.D. Voronyna y D.S. Orlova. Moskva : Yzd. MHU. 118–156 [in russian].

6. Lykov, A.V. (1950) Teoriia sushki [Theory of drying]. Moscow. Gosenergoizdat. 416 p. [in russian].

7. Kolomiiets, S.S., & Yasenchuk, O.V. (2014). Osoblyvosti protsesiv neizotermichnoho masoobminu v gruntakh i perspektyvy yikh vykorystannia v innovatsiinykh ahrotekhnolohiiakh [Peculiarities of non-isothermal mass transfer processes in soils and prospects for their use in innovative agricultural technologies]. *Melioratsiia i vodne hospodarstvo*, 101, 247–2591 [in Ukrainian].

8. Kolomiets, S.S., & Iatsyk, M.V. (2009). Sposib vyznachennia struktury porovoho prostoru gruntiv (dyspersnyh seredovyshch) [Method for determining the structure of porous space of soils (dispersed media)]. Patent of Ukraine. № 45287 [in Ukrainian]

9. Romashchenko, M., & Kolomiiets, S. (2015). Dynamic model of soil functioning and development. Draft book of Abstracts. Soil Science in a Changing World. Wageningen Soil Conference. Wageningen, the Netherlands. P. 228.

10. Kolomiets, S.S. (2021). Termodynamichna systema gruntu, ioho homeostaz i virohidnyj mehanizm utvorennia struktury [Thermodynamic system of soil, its homeostasis and a probable mechanism of structure formation]. *Visnyk agnarnoi nauky,* 3, 14–22 [in Ukrainian].

11. Kolomiets, S.S. (1999). Ekolohichna harakterystyka gruntu [Ecologic characteristic of soil]. *Visnyk agrarnoi nauky,* 12, 9–13 [in Ukrainian].

12. Lower, S. (2022). Solutions of gaseous solutes in liquid solvents]. Simon Fraser University. Retrieved from: https://chem.libretexts.org/@go/page/78395

13. Chaurasia, G. (2023). Nanobubbles: an emerging science in nanotechnology. *Journal of Medical Sciences,* 10 (2), 327–334. DOI: 10.4103/mgmj.MGMJ_59_23.

14. Bulavin, L.A., Kekishev, P., Sysoiev, V.M., & Sheiko, N.L. (2014). Mekhanizm vynyknennia nanobulbashok u vodi na hidrofobnii poverkhni [Mechanism of nanobubbles formation in water on a hydrophobic surface]. *Ukrainskyi fizychnyi zhurnal*, 59 (1), 96–98 [in Ukrainian].

15. Arablousabet, Y., & Povilaitis, A. (2024). The Impact of Nanobubble Gases in Enhancing Soil Moisture, Nutrient Uptake Efficiency and Plant Growth: A Review. *Water,* 16 (21), 3074. DOI: https://doi.org/10.3390/w16213074.

16. Bian, Q., Dong, Z., Zhao, Y., Feng, Y., Fu, Y., Wang, Z., Zhu, J., & Ma, L. (2025). Micro-nanobubble oxygenation irrigation enhances soil phosphorus availability and yield by altering soil bacterial community abundance and core microbial populations. *Front Plant Science,* 15, 1497952. DOI: 10.3389/fpls.2024.1497952.

17. Ouyang, Z., Tian, J., Yan, X.,& Yang, Z., (2023). Micro-nano oxygenated irrigation improves the yield and quality of greenhouse cucumbers under-film drip irrigation. *Scientific Reports,* 13, 19453. DOI: 10.1038/s41598-023-45121-3.

18. Zheng, Z., He, Y., He, Y., Zhan, J., Shi, C., Xu, Y., Wang, X., Wang, J., & Zhang, C. (2025). Micro-nano bubble water subsurface drip irrigation affects strawberry yield and quality by modulation of microbial communities. *Agricultural Water Management,* Vol. 307, 109228. DOI: https://doi.org/10.1016/j.agwat.2024.109228.

УДК 631.4:53.01

КОНЦЕПЦІЯ УЧАСТІ ГАЗІВ У ФОРМУВАННІ ТЕРМОДИНАМІЧНОЇ ДОСТУПНОСТІ ЕЛЕМЕНТІВ ЖИВЛЕННЯ РОСЛИН ТА ПЕРЕБІГУ ҐРУНТОВИХ ПРОЦЕСІВ

С.С. Коломієць[1], канд. с.-г. наук, М.І. Ромащенко[2], докт. техн. наук, А.С. Сардак[3], докт. філософії

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-4329-4382; e-mail: kss2006@ukr.net
[2] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-9997-1346; e-mail: mi.romashchenko@gmail.com;
[3] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-0540-9492; e-mail: anastasiabilobrova1993@gmail.com

«Ґрунт, взятий без газів, не є ґрунтом, хімія ґрунтів не може бути пізнана –
навіть у своїх загальних рисах – вивченням тільки
твердих і рідких складових частин ґрунту»
В.І. Вернадський [1]

Анотація. *Визначено важливу роль газів у планетарному енергомасообміні літосфери з атмосферою, акцентована увага на багатогранних механізмах газообміну, особливо за неізотермічних умов ґрунту. Концептуальні засади участі газів у забезпеченні термодинамічної доступності живлення рослин базуються на експериментальних даних, де акцентована роль газів у гетерогенній системі ґрунтів, для яких характерна наявність бульбашок затиснутого повітря. Адже бульбашки затиснутого ґрунтового повітря у ґрунтовому середовищі відіграють роль розподіленого джерела енергії при взаємодії з термодинамічними параметрами довкілля – температурою, атмосферним тиском та вологовмістом ґрунту. Реакція капілярного потенціалу ґрунту на переважно добову динаміку зовнішніх термодинамічних параметрів має характер автоколивального процесу із значною амплітудою термодинамічної доступності для рослин порового розчину. Це перетворює бульбашки затиснутого повітря у центри термодинамічної нерівноважності (ЦТН), кислотні центри певної сили (КЦ) та центри екотонів ґрунтової біоти. Термодинамічна доступність визначається динамікою гетерогенності ґрунту, тобто його енергонасиченості поверхневими видами енергії, а також підвищенням мобільності речовини і взаємопереходів різних категорій вбирної здатності ґрунтів. Функціональні параметри ґрунту визначає газовий склад ґрунтової атмосфери, де особлива роль належить діоксиду вуглецю (CO_2), як головного чинника підтримання гомеостазу ґрунту. Акцентована увага на тому, що в природних умовах функціонування ґрунту відбувається збагачення складу найдрібніших бульбашок на кисень і нітроген, а найголовніше, розмір цих бульбашок наближається до нанорадіусів, що надає їх аномальних властивостей. На прикладі нанотехнологій з різними газами доведена можливість цілеспрямованого управління ґрунтовими процесами з метою підвищення продуктивності і якості рослинної продукції та меліоративного покращення ґрунтів. Зроблений висновок про надзвичайно високий потенціал інтегрування нанобульбашкових технологій у меліоративне землеробство з використанням сучасних технологій краплинного зрошення.*

Ключові слова: *термодинамічна система ґрунту, ґрунтові процеси, ґрунтові гази, затиснуте повітря, нанобульбашки, енергетика ґрунту, термодинамічна доступність*

DOI: https://doi.org/10.31073/mivg202501-409
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/409

UDC 628.5:574.8:66.098

DEWATERING OF WASTEWATER SLUDGE USING BIOFLOCCULATION

A.B. Mosiichuk, Ph.D. student

Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences, Kyiv, 03022, Ukraine; https://orcid.org/0000-0001-9109-6746; e-mail: andrew.mosiichuk@gmail.com

Abstract. *Sludge dewatering is a crucial stage in wastewater treatment that significantly affects treatment facilities' environmental and economic efficiency. This article explores the issue of wastewater sludge dewatering using bioflocculation, a biotechnology that involves the natural process of particle aggregation involving microorganisms or their metabolites. Biological wastewater treatment remains a leading approach globally and in Ukraine; however, existing sludge dewatering methods face limitations due to high costs and insufficient efficiency. Bioflocculation helps reduce sludge moisture content, increase dry matter concentration, and decrease waste volume, contributing to resource savings and reduced chemical load. The study analyzes the impact of microbial bioflocculants on sedimentation and dewatering processes, particularly exopolysaccharides produced by Bacillus, Pseudomonas, and Klebsiella bacteria. Parameters influencing efficiency, such as dosage, contact time, pH, and aeration, are considered. Combining bioflocculation with conventional methods, such as centrifugation and mechanical thickening, enhances treatment efficiency while reducing energy and reagent consumption. Special attention is given to the potential implementation of bioflocculation at Ukrainian treatment plants, where the local production of microbial bioflocculants could replace synthetic polymers. Key influencing factors – microbial community composition, physicochemical properties of sludge, and cultivation conditions – are analyzed for their impact on process stability. The advantages of bioflocculation are outlined, including environmental friendliness, reduced product toxicity, improved dewatering, and cost reduction. At the same time, challenges such as microbial adaptation, wastewater variability, and the need for further research to implement the technology are acknowledged. Therefore, bioflocculation is a promising approach to improving wastewater treatment and sludge dewatering, aligning with modern environmental standards and supporting sustainable waste management.*

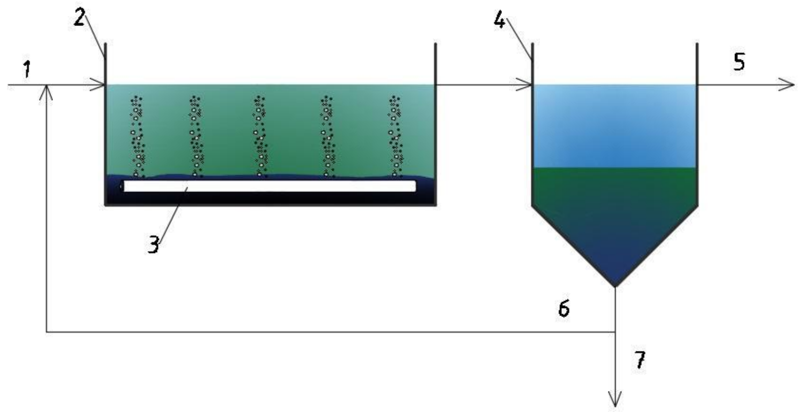
Keywords: *bioflocculation, sludge dewatering, microbial bioflocculants, activated sludge, wastewater, water treatment*

Relevance of research. Biological wastewater treatment methods are among the most widely used globally, where the core of the process is the biological oxidation of organic substances and the accumulation of inorganic compounds by living organisms [1–4]. The microbial biocenosis (a complex community of bacteria, protozoa, algae, fungi, and higher organisms) ensures the self-purification of aquatic ecosystems through metabiosis, symbiosis, and antagonism by mineralizing organic compounds that serve as sources of energy and material for biomass growth [3].

The first wastewater treatment facility using activated sludge was built in England in 1914 (Fig. 1) [5]. The core technology is based on a reactor containing an aerated suspension of microorganisms, a settling tank for separation, and a system for recirculating the sludge. Biological methods are often used with physical and chemical treatment techniques, enhancing overall efficiency.

The advantages of biological treatment include high quality and environmental friendliness; however, the lack of comprehensive theoretical models and the high dependence on personnel qualifications challenge the stable operation of treatment facilities.

A promising modern approach is bioflocculation, a natural process of particle aggregation and sedimentation facilitated by microorganisms or their metabolites. Bioflocculation promotes effective sludge dewatering, reduces operating costs, and improves the quality of treated water, which is particularly important in tightening environmental regulations. Therefore, the scientific substantiation, research, and implementation of effective biological wastewater and sludge treatment technologies remain relevant, timely, and economically advantageous tasks.



1 – water for treatment; 2 – aerotank; 3 – aeration system; 4 – settling tank; 5 – treated water; 6 – sludge recirculation; 7 – removal of excess sludge

Fig. 1. Simplified diagram of a sewage treatment plant system with activated sludge by English researchers E. Ardern and W. Lockett (1914) [6]

Analysis of recent research and publications. Bioflocculation is one of the most promising technologies for wastewater sludge dewatering, showing considerable potential for improving treatment facilities' environmental and economic performance. At the same time, current studies focus on developing and optimizing design and technological solutions for its implementation.

Ahmad et al. [7] demonstrated that the addition of exopolysaccharide-based bioflocculants increases the concentration of dry matter in sludge and significantly improves its filtration characteristics, emphasizing the development of automated bioflocculant dosing systems within secondary clarifier designs. Their results showed effective enhancement of dry matter content up to 20 %, provided uniform distribution of reagents in the working medium is achieved.

The importance of integrating bioflocculation with existing sludge dewatering technologies is highlighted in the research by Kurniawan et al. [8]. The review includes examples of mechanical thickeners, vacuum filters, and centrifuges combined with bioflocculants, which allow energy consumption to be reduced by 20–25 % and help lower operational costs by reducing the need for coagulants and chemical reagents.

Experiments conducted by Mnif and Ben Rebah [9] showed that adding *R. erythropolis* enhances the filtration properties of sludge, increasing the dry matter content to 22.5 %. They noted that the optimal operational cycle for the treatment facilities is 4–6 hours, and regular regeneration of aeration systems and mixers is essential to ensure long-term functionality.

Yu and co-authors [10] investigated the design aspects of aerotanks and sludge mineralizers adapted for bioflocculant use. They emphasized the need for regular cleaning of dosing systems to prevent clogging and maintain process stability. Additionally, they highlighted the formation of stable flocs when using biogenic *Fe(III)*, which further reduces sludge moisture.

Selepe et al. [11] investigated the effectiveness of a bioflocculant derived from *Providencia huaxiensis*, which demonstrated a flocculating activity of 90 %, indicating strong potential for industrial-scale application.

At the same time, Yang et al. [12] reported the effectiveness of the *Klebsiella sp. N-10* strain increased the dry matter content in sludge from 13.1 % to 21.3 % while reducing the specific filtration resistance. They proposed optimal technological parameters for operating treatment systems with bioflocculants:

– maintaining the dosage level within 15–40 mg/L, depending on sludge composition;

– contact time between sludge and bioflocculant ranging from 30 to 60 minutes to achieve complete particle aggregation;

– maintaining pH within the range of 6.8–7.2 to maximize polymer activity.

Peng et al. [13–20] comprehensively reviewed the potential for applying microbial flocculants with physicochemical treatment methods. They explored the effects of the combined use of bioflocculants and aluminum salts, which improved the structural stability of flocs and enhanced their dewaterability.

In Ukraine, research on bioflocculation remains mostly at the laboratory stage. For example, Klimenko and Sabliy analyzed physicochemical methods in combination with biotechnology. Still, the integration of bioflocculants into treating wastewater sludge with a high content of organic pollutants was not investigated [21–25].

Despite significant research, integrating bioflocculation into existing technological schemes requires further justification, particularly for the specific operating conditions of treatment plants in different regions.

The purpose of the research is to evaluate the effectiveness of bioflocculation as a sludge dewatering technology using microbial bioflocculants, to identify the key factors influencing process efficiency, and to justify the feasibility of its implementation at wastewater treatment plants in Ukraine.

Research materials and methods. To systematize data on bioflocculation for sewage sludge dewatering, the results of experimental studies presented in foundational works in this field were analyzed. The research methodology examined treatment systems currently in use in Ukraine, focusing on modeling potential outcomes of bioflocculation implementation. Particular attention was given to comparing the technological parameters of sludge mineralizers with the recommended conditions for bioflocculation application, specifically dosage, contact time, aeration conditions, and maintenance of optimal physicochemical parameters.

Calculations were conducted based on actual data from a potential pilot project involving bioflocculants at one of the treatment lines of a wastewater treatment facility in the Rivne region, Ukraine.

To evaluate the effectiveness of bioflocculation, the following formula was used [26]:

$$E = \frac{C_0 - C_f}{C_0} \cdot 100\,\%, \tag{1}$$

where C_0 is the initial concentration of sewage sludge quality indicators, and C_f is the final concentration of sewage sludge quality indicators after bioflocculation.

Research results and their discussion. Bioflocculation is the process of aggregating fine dispersed particles into larger aggregates through the action of microorganisms or the biopolymers they secrete. These macromolecules form a hydrophilic matrix in which water is tightly bound, making its release from the sludge more difficult. The addition of biological flocculants leads to larger aggregates and compression of the electric double layer on particle surfaces. As a result, extracellular polymers break down, releasing bound water and enhancing sludge dewatering [9]. Charge neutralization and the formation of inter-particle "bridges" between polysaccharide chains further stabilize the flocs [12]. The primary mechanisms of bioflocculation include:

– electrostatic interactions between microorganisms and particles;

– secretion of exopolysaccharides that promote floc formation;

– hydrophobic interactions and complexation between microorganisms and pollutants.

Bioflocculants are classified into microbial flocculants (bacteria, fungi), polysaccharide-based, protein-based, and combined bioflocculants.

The main factors influencing the bioflocculation process are the composition of the microflora, the chemical makeup of the sludge (presence of organic and inorganic compounds affecting floc formation), physicochemical conditions, and the use of biopolymers.

The composition of the wastewater sludge microflora is a critically important factor influencing the bioflocculation process. Microorganisms present in sludge act as primary agents facilitating particle aggregation. Bacteria such as *Acinetobacter*, *Pseudomonas*, and *Bacillus* (see Fig. 2) and fungi like *Aspergillus* and *Penicillium* actively produce biopolymers that aid flocculation. A high concentration of exopolysaccharide-producing bacteria positively affects the formation of dense and stable flocs. Elevated metabolic activity among microorganisms enhances aggregation efficiency, as active cells more effectively interact with contaminants and promote sedimentation. The dominance of particular microorganism species can either enhance or hinder bioflocculation. For instance, some species may be less effective in producing flocculating substances or may even disrupt already-formed flocs. Microflora is sensitive to changes in pH, temperature, nutrient concentration, and toxic substances in the wastewater; optimal conditions ensure maximum activity and high-quality floc formation.

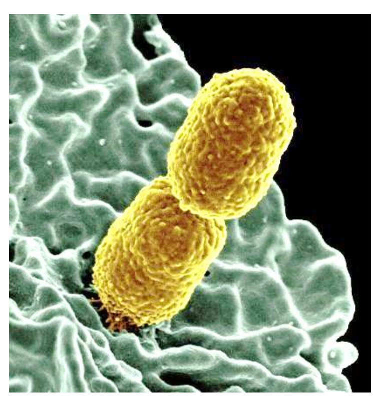


Fig. 2. Bacterial bioflocculant *Bacillus sp.*

Combining different microorganisms can form more effective bioflocculants due to the mutual enhancement of exopolymer release.

Considering these factors, the selection and optimization of the microbial composition of wastewater sludge is one of the key directions for improving the efficiency of bioflocculation. Research focused on microbial community composition and its role in aggregation processes will enable the development of new approaches to enhancing sludge dewatering technologies. For effective implementation of bioflocculation in wastewater treatment processes, the following aspects must be taken into account:

– use of activated sludge: activated sludge can serve as a source of bioflocculants to enhance sedimentation and dewatering;

– application of natural bioflocculants: using biopolymers based on exopolysaccharides to enhance coagulation and particle aggregation;

– combination with other methods: integrating bioflocculation with flotation, electrocoagulation, or ultrasonic treatment can improve treatment efficiency;

– optimization of process conditions: adjusting pH, temperature, aeration, and nutrient content to maximize bioflocculant productivity.

Bioflocculation technology can be implemented in existing aerotanks or anaerobic sludge tanks, where activated sludge already contains microorganisms capable of producing bioflocculants. Among the possible structural components of wastewater sludge dewatering technologies, activated sludge mineralizers have been identified as promising facilities for the application of bioflocculation. In mineralizers, activated sludge accumulates and stabilizes before being fed to sludge drying beds. Reducing volume and increasing dry solids concentration at this stage directly impacts subsequent dewatering and sludge disposal. Adding bioflocculants directly into mineralizers will provide the best effect, as the sludge is not yet dewatered, and the stabilization process allows for the even distribution of reagents.

Internal production of flocculants by bacteria reduces the need for expensive synthetic polymeric flocculants. It increases the environmental friendliness of the process, avoiding contamination of the sludge with heavy metals and by-products of incomplete synthesis, which are characteristic of some chemical coagulants. Considering that the synthesis of bacterial biopolymers is slower than chemical precipitation, the actual effect may appear over a more extended period than traditional coagulants.

Overall, bioflocculation can increase dry matter concentration in sludge and reduce its volume, facilitating transport and disposal. However, increased nutrient content for bacteria may promote the growth of filamentous or coliform bacteria, which can cause sludge swelling and foaming. Therefore, the production of bioflocculants and cultivation conditions (temperature, pH, nutrient availability) must be carefully controlled.

At the same time, the adaptation time for microorganisms, maintaining optimal process conditions, and potential variations in effectiveness depending on wastewater composition limit the use of bioflocculation and highlight the need for further research. Optimization of the bioflocculation process is possible by selecting effective bioflocculants by wastewater quality indicators, controlling their concentration in the system, and using mathematical models to predict process efficiency.

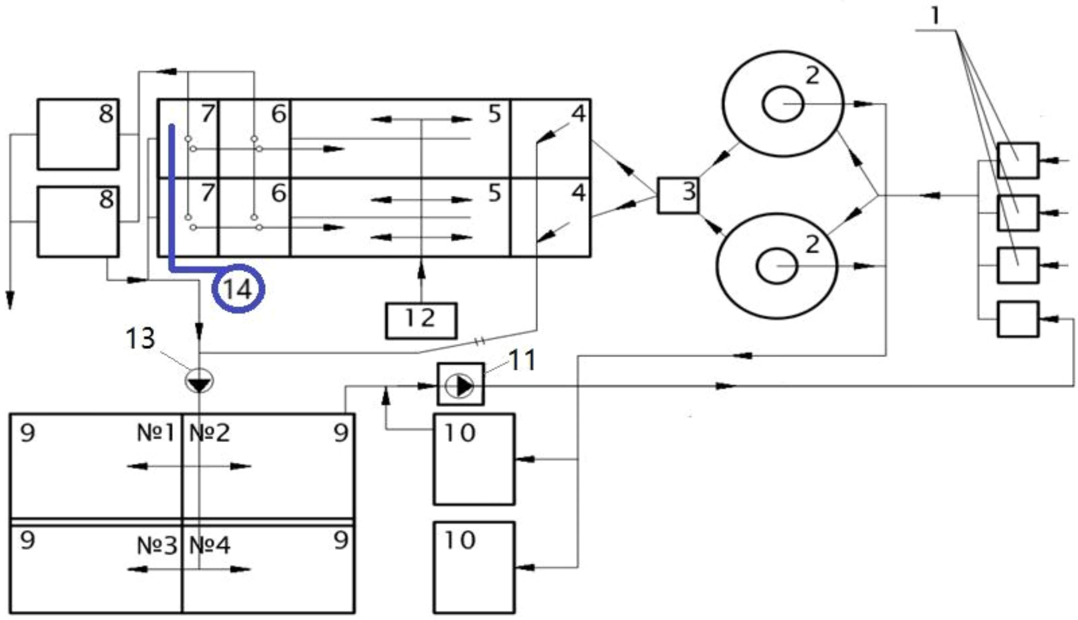
For effective implementation of bioflocculation in sludge mineralizers, it is necessary to consider the design of the mineralizer, the dosing system, regeneration process parameters, and flushing, as well as configure process parameter control.

Existing facilities should be adapted to allow for uniform dosing of bioflocculants. Dosing systems can be integrated into existing sludge feed channels, ensuring optimal flocculant concentrations (10–50 mg/L depending on sludge volume). The use of automatic dosing units ensures even distribution of reagents throughout the volume of the mineralizer. Liquid bioflocculants are preferred due to their short dissolution time and high activity.

The contact time between the sludge and the bioflocculant should be between 30 and 60 minutes. Aeration systems or mechanical stirrers are recommended to ensure uniform mixing. After each processing cycle, the mineralizer should be flushed to prevent the accumulation of residual substances. The duration of flushing should be at least 15 minutes.

Determining the optimal *pH* level (6.5–7.5), temperature (20–30 °C), and nutrient concentration is critical for the adequate performance of bioflocculants.

Considering the use of sludge mineralizers as potential facilities for the implementation of bioflocculation, the technological scheme of wastewater treatment plants will include mechanical treatment (three receiving chambers, mechanical grids, sand traps, sand drying beds, distribution chamber; radial primary clarifiers), biological treatment (two-channel aerotanks; radial secondary clarifiers; blowers; sludge pumps), wastewater disinfection (contact tanks), and sludge treatment (mineralizers; sludge drying beds with flushing drainage) (Fig. 3). To predict the effectiveness of bioflocculants at the sludge dewatering stage, sludge indicators before and after the implementation of bioflocculation are compared.



1 – Receiving chambers; 2 – Sand traps; 3 – Distribution chamber; 4 – Primary clarifiers; 5 – Aerotanks; 6 – Secondary clarifiers; 7 – Mineralizers; 8 – Contact tanks; 9 – Sludge drying beds; 10 – Sand drying beds; 11 – Drainage pumping station; 12 – Blower (air supply) pumping station; 13 – Raw sludge pumping station; 14 – Bioflocculant dosing point

Fig. 3. Predictive technological scheme of wastewater treatment facilities with sludge bioflocculation

Bioflocculants are introduced in liquid or dry form at an optimal dosage through special mixers or dosing systems to ensure uniform distribution.

The key design indicators for implementing the technology include sludge moisture content, the concentration of dry solids, the volume of dewatered sludge, and the content characteristics of heavy metals and organic matter.

Sludge moisture content (%) is calculated using the following formulas:

– without bioflocculation

$$W_1 = \frac{m_w}{m_{tot}} * 100, \quad (2)$$

– with bioflocculation

$$W_2 = W_1 * (1 - \Delta W), \quad (3)$$

where m_w is the mass of water in the sludge, m_{tot} is the total mass of the sludge, and ΔW is the projected decrease in moisture content.

Dry solids concentrations (%):

– without bioflocculation

$$S_1 = \frac{m_d}{m_{tot}} * 100, \quad (4)$$

– with bioflocculation

$$S_2 = S_1 * (1 + \Delta S), \quad (5)$$

where m_d is dry solids mass, and ΔS is the projected increase in dry solids concentration.

The volume of dewatered sludge (m³):

– without bioflocculation

$$V_1 = \frac{m_{tot}}{\rho_s}, \quad (6)$$

– with bioflocculation

$$V_2 = V_1 * (1 - \Delta V), \quad (7)$$

where ρ_s is sludge density, and ΔV is projected volume reduction.

Forecast of heavy metals and organic content is based on the expected reduction in toxic compounds and improved sludge stability (%):

$$C_n = C_1 * (1 - \Delta C), \quad (8)$$

where C_n is the concentration of the n-th component, C_1 is the component without bioflocculation, and ΔC is expected to decrease in component concentration.

The calculation data is included in the predictive table.

Calculated qualitative and quantitative sludge indicators for scenarios with and without bioflocculation

Indicator	Without bioflocculation	With bioflocculation
Dry solids concentrations (%)	2–4	5–7
Sludge moisture content (%)	96–98	93–95
Sludge volume (m³/day)	250–300	200–240
Nitrogen (*N*, mg/kg)	10–15	8–12
Phosphorus (*P*, mg/kg)	20–25	18–22
Organic carbon (*C*, mg/kg)	150–200	120–180
Required sludge drying beds (m²)	1000–1200	800–1000

The projected changes in indicators demonstrate the advantages of implementing bioflocculation:

– increased concentration of dry solids (bioflocculants promote the formation of compact flocs that are easier to dewater);

– more efficient water removal reduces sludge volume and the need for sludge drying bed areas;

– the resulting flocs are more stable, decreasing the risk of rehydration and improving the overall sludge structure.

Since bioflocculation involves using microorganisms (particularly filamentous bacteria) that actively interact with suspended sludge particles, one of the key parameters for laboratory monitoring is the content of pathogenic organisms in the sludge. During the process, dense aggregates are formed in which pathogens may become mechanically encapsulated or remain free, depending on their characteristics. Filamentous bacteria create a three-dimensional matrix within the sludge structure, which can trap pathogens and restrict their access to nutrients. At the same time, anaerobic conditions develop within the flocs, which may reduce the viability of aerobic pathogens. However, such conditions may be favorable for persistent anaerobic pathogens.

If bioflocculation is effective, pathogens may be mechanically separated along with the sludge during dewatering. The formation of large, dense aggregates may also inhibit the survival of certain pathogenic microorganisms.

Conclusions. Bioflocculation is a promising method for improving the dewatering of wastewater sludge, enabling reduced environmental impact and enhanced treatment efficiency. Implementing this technology can decrease the need for chemical reagents, improve sludge processing quality, and enhance the ecological safety of wastewater treatment facilities.

To implement bioflocculation, existing sludge mineralization units must be adapted by integrating automatic dosing and process parameter control systems tailored to the specific conditions of Ukrainian treatment plants. Further research should focus on optimizing process parameters and the implementation of bioflocculants capable of functioning under a wide range of conditions. The successful application of bioflocculation may become a vital tool for sustainable water resource management in Ukraine.

References

1. California Water Plan Highlights. Department of Water Resources Bulletin 160-05. 2005.
2. Tavartkiladze, I.M., Tarasiuk, T.P., & Dotsenko, M.I. (1988). Ochisni sporudy vodovidvedennia: Dovidnyk [Sewerage treatment facilities: Reference book]. Kyiv: Budivelnyk. [in Ukrainian].
3. Kulskii, L.A. (1976). Khimiia i mikrobiolohiia vody [Chemistry and microbiology of water] [in Russian].
4. Toralova, Y., Ribarova, I., Dimkov, R., & Arsov, R. (1995) Upgrading of a small wastewater treatment plant: design & operation. *Water Sci. Tech*. Vol. 32, № 7, 111–117.
5. Water Treatment Handbook (2 Volumes set, 7th Ed.) (2007). Degrémont.
6. Mosiichuk, Ya.B. (2020). Udoskonalennia tekhnolohii ochyshchennia i vykorystannia stichnykh vod u silskii mistsevosti [Improvement of wastewater treatment and utilization technologies in rural areas] [Doctoral dissertation, Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine] [in Ukrainian].
7. Ahmad, J., Mohd Said, N.S., Ramli, N.N., Buhari, J., Abdullah, S.R.S., Othman, A.R., Wan Jusoh, H.H., Juahir, H., & Kurniawan, S.B. (2024). A review on the roles of extracellular polymeric substances (EPSs) in wastewater treatment: *Source, mechanism study, bioproducts, limitations, and future challenges. Water*, 16 (19), 2812. DOI: https://doi.org/10.3390/w16192812

8. Kurniawan, S.B., Abdullah, S.R.S., Imron, M.F., Said, N.S.M., Ismail, N., Hasan, H. A., Othman, A.R., & Purwanti, I.F. (2020). Challenges and Opportunities of Biocoagulant/Bioflocculant Application for Drinking Water and Wastewater Treatment and Its Potential for Sludge Recovery. *International Journal of Environmental Research and Public Health*, 17 (24), 9312. DOI: https://doi.org/10.3390/ijerph17249312

9. Mnif, W., & Ben Rebah, F. (2023). Bioflocculants as alternative to synthetic polymers to enhance wastewater sludge dewaterability: A review. Energies, 16 (8), 3392. DOI: https://doi.org/10.3390/en16083392

10. Yu, L., Tang, Q.-w., Zhang, Y.-j., Chen, R.-p., Liu, X., Qiao, W.-c., Li, W.-w., Ruan, H.-h., & Song, X. (2016). A novel Fe(III) dependent bioflocculant from Klebsiella oxytoca GS-4-08: culture conditions optimization and flocculation mechanism. *Scientific Reports*, 6 (1). https://doi.org/10.1038/srep34980

11. Selepe, T.N., Maliehe, T.S., Moganedi, K., Masoko, P., & Mulaudzi, V. (2022). Isolation and Optimisation of Culture Conditions for a Marine Bioflocculant-Producing Bacterium and Application of Its Bioflocculant in Wastewater Treatment. *International journal of environmental research and public health*, 19 (16), 10237. DOI: https://doi.org/10.3390/ijerph191610237

12. Yang, Q., Luo, K., Liao, D.-X., Li, X.-M., Wang, D.-B., Liu, X., & Xu, L. (2012). A novel bioflocculant produced by Klebsiella sp. and its application to sludge dewatering. *Water and Environment Journal*, 26 (3), 560–566. DOI: https://doi.org/10.1111/j.1747-6593.2012.00319.x

13. Peng, L., Yang, C., Zeng, G., Wang, L., Dai, C., Long, Z., Liu, H., & Zhong, Y. (2014). Characterization and application of bioflocculant prepared by Rhodococcus erythropolis using sludge and livestock wastewater as cheap culture media. *Applied microbiology and biotechnology*, 98 (15), 6847–6858. DOI: https://doi.org/10.1007/s00253-014-5725-4

14. Ntsangani, N., Okaiyeto, K., Uchechukwu, N.U., Olaniran, A.O., Mabinya, L.V., & Okoh, A.I. (2017). Bioflocculation potentials of a uronic acid-containing glycoprotein produced by Bacillus sp. AEMREG4 isolated from Tyhume River, South Africa. *3 Biotech*, 7 (1), 78. DOI: https://doi.org/10.1007/s13205-017-0695-8

15. Kurade, M.B., Murugesan, K., Selvam, A., Yu, S.M., & Wong, J.W. (2016). Sludge conditioning using biogenic flocculant produced by Acidithiobacillus ferrooxidans for enhancement in dewaterability. *Bioresource technology*, 217, 179–185. DOI: https://doi.org/10.1016/j.biortech.2016.02.113

16. Agunbiade, M.O., Van Heerden, E., Pohl, C.H. et al. Flocculating performance of a bioflocculant produced by Arthrobacter humicola in sewage waste water treatment. *BMC Biotechnol,* 17, 51 (2017). DOI: https://doi.org/10.1186/s12896-017-0375-0

17. Fujita, M., Ike, M., Tachibana, S., Kitada, G., Kim, S.-M., & Inoue, Z. (2000). Characterization of a bioflocculant produced by Citrobacter sp. TKF04 from acetic and propionic acids. *Journal of Bioscience and Bioengineering,* 89 (1), 40–46. DOI: https://doi.org/10.1016/S1389-1723 (00)88048-2

18. Dai, J., Zhao, X., Mu, S., Yang, Q., Zhao, C., & Zhao, Z. (2024). A novel polysaccharide-based bioflocculant produced by Bacillus subtilis 35A and its application in the treatment of dye decolorization, heavy metal ion adsorption and meat product wastewater. *Frontiers in Microbiology*, 15. DOI: https://doi.org/10.3389/fmicb.2024.1457909

19. Arimieari, L., & Ademiluyi, J. (2018). Sludge filtration resistance model based on electrical resistance analogy. Journal of Environmental Protection, 9, 1–12. https://doi.org/10.4236/jep.2018.91001

20. Guo, J., Liu, J., Yang, Y., Zhou, Y., Jiang, S., & Chen, C. (2018). Fermentation and kinetics characteristics of a bioflocculant from potato starch wastewater and its application. *Scientific reports*, 8 (1), 3631. DOI: https://doi.org/10.1038/s41598-018-21796-x

21. Sabliy, L.A. (2013). Fiziko-khimichne ta biolohichne ochyshchennia vysokokoncentrovanykh stichnykh vod: Monohrafiia [Physical and chemical and biological treatment of high-concentration wastewater: Monograph]. Rivne: NUVHP [in Ukrainian].

22. Koganovskii, A.M., Klimenko, N.A., Levchenko, T.M., et al. (1983). Ochistka i ispolzovanie stochnykh vod v promyshlennom vodosnabzhenii [Treatment and use of wastewater in industrial water supply]. Moskva: Khimiia [in Russian].

23. Zapolskii, A.K., Mishkova-Klimenko, N.A., Astrelin, I.A., et al. (2000). Fiziko-khimichni osnovy tekhnolohii ochyshchennia stichnykh vod [Physicochemical foundations of wastewater treatment technology] (A.K. Zapolskii, Ed.). Kyiv: Libra [in Ukrainian].

24. Klimenko, N.A., & Kozhanov, V.A. (1991). Kolloidno-khimicheskie aspekty formirovaniia sostava stochnykh vod tekstilnykh predpriiatii i vozmozhnye metody ikh ochistki [Colloidal-chemical aspects of the formation of the composition of wastewater from textile enterprises and possible treatment methods]. Khimia i tekhnologiia vody, 13 (7), 579–592. [in Russian].

25.Sabliy, L.A., & Zhukova, V.S. (2008). Vdoskonalennia roboty kanalizatsiinykh ochysnykh sporud [Improving the operation of sewer treatment facilities]. *Vodopostachannia ta vodovidvedennia*, (5), 33–36 [in Ukrainian].
26.Khoruzhii, P.D., Khomutetska, T.P., & Khoruzhii, V.P. (2008). Resursosberihaiochi tekhnolohii vodopostachannia [Resource-saving water supply technologies]. Kyiv: Ahrarna nauka [in Ukrainian].

УДК 628.5:574.8:66.098

ЗНЕВОДНЕННЯ ОСАДІВ СТІЧНИХ ВОД З ВИКОРИСТАННЯМ БІОФЛОКУЛЯЦІЇ

А.Б. Мосійчук, аспірант

Інститут водних проблем і меліорації НААН, м. Київ, 03022, Україна;
https://orcid.org/0000-0001-9109-6746; e-mail: andrew.mosiichuk@gmail.com

Анотація. *Зневоднення осадів стічних вод є важливим етапом очищення, що значно впливає на екологічність і економічність роботи очисних споруд. У статті досліджується проблема зневоднення осадів стічних вод із застосуванням біофлокуляції – біотехнології, що базується на природному процесі агрегації частинок за участі мікроорганізмів або їх метаболітів. Біологічне очищення стічних вод залишається провідним напрямом у світі та Україні, проте існуючі методи зневоднення осадів мають обмеження через високі витрати та недостатню ефективність. Біофлокуляція дозволяє знизити вологість осаду, підвищити концентрацію сухих речовин і зменшити об'єм відходів, що сприяє економії ресурсів та зменшенню хімічного навантаження. У роботі проаналізовано вплив різних мікробних біофлокулянтів, зокрема екзополісахаридів бактерій Bacillus, Pseudomonas, Klebsiella, на процеси осадження та зневоднення. Розглянуто параметри, що впливають на ефективність, зокрема дозування, час контакту, pH і аерацію. Поєднання біофлокуляції з традиційними методами, такими як центрифугування і механічне ущільнення, підвищує ефективність очищення, знижуючи споживання енергії і реагентів. Особливу увагу приділено можливостям впровадження біофлокуляції на очисних спорудах України, де внутрішнє виробництво біофлокулянтів мікроорганізмами може замінити синтетичні полімери. Проаналізовано ключові чинники – склад мікрофлори, фізико-хімічні властивості осаду, умови культивування – що впливають на стабільність процесу. Визначено переваги біофлокуляції: екологічність, зниження токсичності продуктів, покращене зневоднення і зниження витрат. Водночас відзначено виклики, пов'язані з адаптацією мікроорганізмів, варіабельністю стічних вод і потребою подальших досліджень для впровадження технології. Отже, біофлокуляція є перспективним напрямом для підвищення ефективності очищення стічних вод і зневоднення осадів, що відповідає сучасним екологічним вимогам і сприяє сталому управлінню відходами.*
Ключові слова: *біофлокуляція, зневоднення осадів, мікробні біофлокулянти, активний мул, стічні води, очищення води*

DOI: https://doi.org/10.31073/mivg202501-411
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/411

UDC 631.67

ESTIMATION OF THE ACCURACY OF THE CALCULATION OF REFERENCE AND ACTUAL EVAPOTRANSPIRATION BASED ON VIRTUAL WEATHER STATION DATA FOR POLISSYA REGION OF UKRAINE

O.V. Zhuravlov[1], Dr. of Agricultural Sciences, A.P. Shatkovskyi[2], Dr. of Agricultural Sciences, M.V. Scherbatiuk[3], V.V. Liubitskyi[4], V.V. Karuna[5]

[1] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0001-7035-219X ; e-mail: zhuravlov_olexandr@ukr.net;
[2] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0000-0002-4366-0397; e-mail: andriy-1804@ukr.net;
[3] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0009-0009-1784-6639; e-mail: sherbatuykmaksim@gmail.com;
[4] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0009-0000-2412-1454; e-mail: v.liubitskyi@agro-fk.com.ua;
[5] Institute of Water Problems and Land Reclamation NAAS, Kyiv, 03022, Ukraine;
https://orcid.org/0009-0005-6162-5391; e-mail: karuna@ukr.net

Abstract: *This article evaluates the accuracy of calculating reference and actual evapotranspiration using Virtual Visual Crossing Weather Data (VCWD) and automatic iMetos Base meteorological station data in Polissya, Ukraine. The study confirmed the feasibility of calculating ETo and ETc using VCWD meteorological data. The ETo calculation is 86,1 % accurate, with an RMSE and SEE error of 0,76 and 0,49 mm, respectively. The ETo calculation with correction factors for meteorological data increases its accuracy by 1,4 %, and the RMSE error decreases by 0,08 mm. The most accurate calculations were obtained using a correction factor of 1,1 to the calculated ETo. With the correction factor applied, the ETo determination accuracy is 88,9 %, with RMSE and SEE errors of 0,58 and 0,54 mm, respectively. The ETo data from VCWD were obtained with satisfactory accuracy; the largest errors in the MAPE, RMSE, and SEE were 20,4 %, 1.09 mm, and 1,02 mm, respectively. For 2023–2024, the FEA, RMSE, and SEE errors for ETo calculated from VCWD meteorological data, accounting for the 1,1 correction factor, were 10,0–12,2 %, 0,55–0,60, and 0,51–0,55 mm, respectively. During the research period, the MAPE, RMSE, and SEE errors for this variant were 9,0 %–14,0 %, 0,52–0,63 mm, and 0,34–0,56 mm, respectively. The calculation of absolute errors in determining ETo confirms that the most reliable data of reference evapotranspiration are obtained using the correction factor. This option resulted in the smallest average absolute error by years of research, which is 5 mm, and in 2024 this error was 0. In terms of months, the smallest absolute error of 2 mm was observed in May and August, and the largest –13 mm in September.*

The results of the calculations of actual evapotranspiration (ETc) of crops showed that using a correction factor of 1,1 to ETo increases the accuracy of ETc calculations. The mean absolute relative error (MAPE) decreased by 2,1 % for all crops, and the root mean square error (RMSE) decreased by 0,16, 0,15, and 0,09 mm for corn, potatoes, and blueberries, respectively. The average absolute ETc errors by year of research using a correction factor of 1,1 for ETo were 15,7, and 11 mm for corn, potatoes, and blueberries, respectively. In May, June, and July, the calculated ETc for corn seed was 11,6, and 8 mm lower than the actual values. In August and September, it was 1 and 9 mm higher, respectively. This trend in the errors distribution is also observed for potatoes and blueberries.

Keywords: *virtual weather station, reference evapotranspiration, actual evapotranspiration, corn, potatoes, blueberries, accuracy, IEA errors, RMSE errors, and SEE errors*

Relevance of the study. The Penman – Monteith method (FAO56-PM) is widely used in irrigation management today. While the use of various meteorological data is an advantage of this method, it is also a disadvantage because not all the necessary data are always available. This is because not all the meteorological data necessary for calculating reference evapotranspiration (ETo) using the Penman-Monteith method are always available. ETo is most often calculated using automated weather stations (AWS), but these must be equipped with all the necessary climate sensors, which increases their cost, which is already considerable. The sensors used at AWS must be periodically checked and have a service life of 3–5 years. During operation, it is necessary to monitor the sensors and clean them periodically, as well as monitoring the station's power supply, especially in winter. In the absence of communication, there is a risk of data loss, and the range of the AWS is up to 5 km or 8 thousand hectares.

Given the high cost of AWS and all its shortcomings, the calculation of ETo by the Penman-Monteith method using data from virtual weather stations (VWS) is of practical importance. The Visual Crossing Weather Data (VCWD) virtual weather station was chosen to calculate the ETo. It provides easy access to hourly or daily climate data for the entire world, including forecast data for the next 15 days. Its archive includes more than 50 years of global weather history. In addition to the usual meteorological indicators, such as temperature and relative humidity, wind speed, precipitation, powerful features such as solar radiation and energy, degree days, reference evapotranspiration, and weather forecast are available. All data from the site is available for download via the weather data request page and the weather API. The datasets are displayed in a table, which is available in several formats. One of the powerful features of VCWD is the ability to import data into most business intelligence systems, Excel and others for further processing.

Analysis of recent research and publications. Much attention has been paid to the issue of determining crop evapotranspiration (ETc) and its accuracy [1, 2]. Accurate estimation of reference evapotranspiration (ETo) is crucial for determining crop water requirements. However, the lack of appropriate weather stations, especially in arid areas, can negatively affect the accuracy of ETc estimates. Studies conducted in the Persian Gulf and Gulf of Oman basin (western and southwestern Iran) [3] to evaluate the performance of three datasets ERA5, ERA5-Land, and WaPOR for ET estimation emphasize that ERA5 demonstrates better overall performance compared to other datasets in ET estimation. However, WaPOR performed better at high-altitude stations with heterogeneous topography than the reanalysis of ERA5 and ERA5-Land. Thus, none of the datasets could provide accurate ETo estimates for all stations within the basin. Studies evaluating the accuracy of the daily reference evapotranspiration [4] calculated using NASA POWER reanalysis products in the Mediterranean climate (southern Portugal) indicate that when using the raw NASA POWER datasets, good accuracy between the calculated and observed ETo was observed at most locations. The LSA-SAF products [5] showed a high potential for accurate ETo calculation for continental Portugal, but low accuracy for the Azores. The study [6] evaluated the data quality of GLDAS-1, NLDAS-2, CFSv2, gridMET, RTMA, and NDFD weather products for ETo calculation. The results were compared with 103 weather stations located in well-moistened areas of the United States. ETo and the climate data used to calculate it were compared. The meteorological datasets from virtual weather stations overestimate the reference evapotranspiration obtained from ground-based weather stations, with an average deviation ranging from 12 to 31 %. The overestimation is mainly due to overestimation of air temperature, shortwave radiation, wind speed, and underestimation of relative humidity. These results indicate that virtual weather station data should be carefully evaluated before replacing agricultural weather station data. Correction procedures can make virtual weather station data more suitable for ETo calculation. Current evapotranspiration estimation methods are typically based on ETo calculations using data from scattered weather stations, many of which may be located in partially or totally dry environments with no evaporation. Such data and the calculated ETo may suffer from a shift in aridity relative to the ETo characteristic of irrigated conditions. Study [2] developed an algorithm for processing climate data to quantify the impact of surface aridity on the calculation of reference evapotranspiration. The conditioning algorithm is based on standard equations of the surface energy balance and the relationship between the flow and profile of air masses, which can be applied to both point weather station data and virtual weather station weather datasets. The calculation of the reference evapotranspiration using the Penman-Monteith equation requires extended weather data, but the relevant datasets are often unavailable, incomplete, or of uncertain quality. The study [7] discusses computational procedures related to the prediction of missing variables from temperature, i.e., the RM temperature approach (RMTA) and the estimation of ETo using the Hargreaves-Samani (HS) equation. Since the results of ETo in the HS equation depend almost linearly on air temperature, the RMT approach, which uses climate data estimates, is able to mitigate these temperature effects. An obvious advantage of the RMT approach is that it allows the use of available weather data in combination with estimates of missing data, which results in more accurate ETo calculations.

The calculation of actual evapotranspiration (ETa) usually requires the measurement of several atmospheric and evaporative surface variables. In a linear generalized model (GLM), the dependent variable is linearly related to the factors and co-variables through functional relationships. To calculate the daily actual evapotranspiration (ETa) of barley crops in the eastern Argentine Pampa, data from the meteorological and energy balance were used [8]. A linear generalized model (GLM) was obtained to calculate ETa from using meteorological data measured at the stations. The model has shown good efficacy and can be applied and tested on other large plains.

Quantifying water consumption by the agricultural sector requires continuous monitoring at different spatial scales from one hectare to a basin. However, providing spatially distributed information for large areas makes the use of on-site measuring devices impossible. Earth observation satellites and remote sensing techniques offer an effective alternative in assessing water use. However, in order to implement an operational monitoring system based on remote sensing data, it is necessary to establish approaches with reliable protocols to obtain information at the required spatial and temporal scale [9]. Landsat imagery combined with the METRIC model is used in the EEFlux program to estimate actual evapotranspiration in irrigated areas, with uncertainty as to whether the results are sufficiently accurate at local scales. A study to assess the accuracy of the obtained indicators was conducted for irrigated areas in the northern state of Sinaloa (Mexico) from 1995 to 2018 [10], comparing temporal and spatial estimates using Landsat images and the METRIC model with locally measured weather data and EEFlux. The results of the analysis confirm differences that are closely related to crop growth, with a daily average absolute error of 1.17 mm/day. The spatial analysis showed that when using only arable land pixels without non-arable land pixels in EEFlux, R^2increases from 0,36 to 0,73 and RMSE decreases from 2,52 to 1,98 mm/day.

The aim of the study was to assess the accuracy of the calculations of reference (ETo) and actual (ETs) evapotranspiration according to the data of the virtual weather station Visual Crossing Weather Data (VCWD) and compare them with the actual data obtained from the automated Internet weather station iMetos base.

Materials and methods. The meteorological data for this study were obtained from VWS Visual Crossing Weather Data [11] for the period 2023-2024 and from AWS iMetos Base from Pessl Instruments [12], which is located at the experimental site of LLC "Agrofirma Kyivska", Makovyshche village, Makariv district, Kyiv region (50.4574°N, 29.8949°E).

To analyze and calculate the reference evapotranspiration (ET_0), the average daily meteorological data: average air temperature (Ta) and dew point (Tdew), wind speed (u_2) and total solar radiation (Rs) were used. The reference evapotranspiration, based on VCWD meteorological data, was calculated using the Penman-Monteith FAO56-PM method [13]:

$$ET_0 = \frac{0,408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0,34u_2\right)}. \quad (1)$$

where ET_0 is the reference evapotranspiration, mm/day; *Rn* is the net radiation on the plant surface, MJ/m^2-day; *G* is the density of the soil heat flux, MJ/m^2-day; *Ta* is the average daily air temperature at a height of 2 m, °C; $u_{(2)}$ is the wind speed at a height of 2 m, m/s; $e_{(s)}$ is the saturated vapor pressure, kPa; $e_{(a)\ is}$the actual pressure, kPa; Δ is the gradient of the vapor pressure curve, kPa/° C; γ is the psychometric constant, kPa/C.

To calculate $e_s$and $e_{(a)}$ the mean air temperature and dew point values were used, respectively. The average wind speed was calculated for a height of 2 m. The other parameters included in formula (1) were calculated according to the FAO56-PM methodology [13].

The calculated reference evapotranspiration was compared with the actual ET_0 obtained from the AWS iMetos database.

Crop evapotranspiration was calculated using the formula [13]:

$$ET_C = ET_0 \cdot K_C. \quad (2)$$

where ET_C is evapotranspiration, mm/day; K_C is the crop coefficient.

Tossess the accuracy of the calculations of the reference and actual evapotranspiration, the MAPE (Mean Absolute Percent Error), RMSE (Root Mean Square Error), SEE (Standard Error of Estimate), and AE (Absolute Error) were determined [14–17]:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x-y}{x}\right| \cdot 100\%. \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x-y\right)^2}. \quad (4)$$

$$SEE = \sqrt{\frac{1}{(n-2)}\left[\left(y-\bar{y}\right)^2 - \frac{\left[\Sigma\left(x-\bar{x}\right)\left(y-\bar{y}\right)\right]^2}{\Sigma\left(x-\bar{x}\right)^2}\right]}. \quad (5)$$

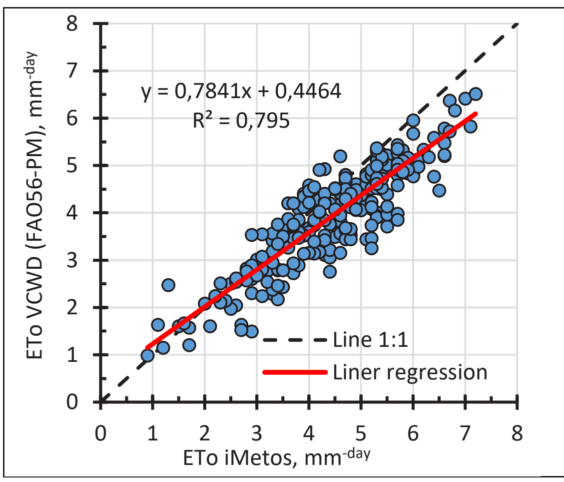
$$AE = x - y. \quad (6)$$

$$Accuracy(\%) = 100\% - MAPE(\%) \quad (7)$$

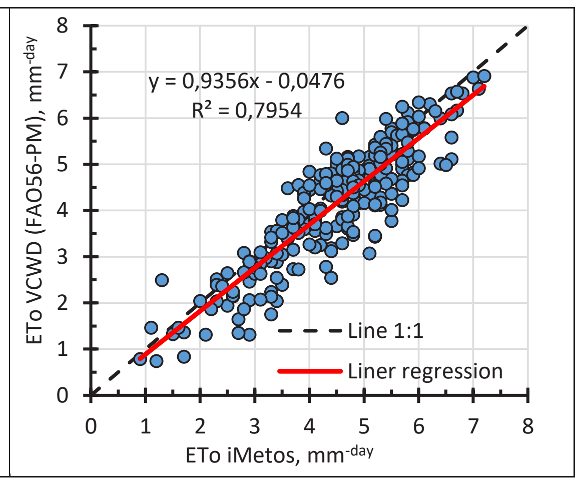
where x – $ET_{(0)}$ or ET_C according to the iMetos Internet weather station; y – $ET_{(0)}$ or ETc calculated according to VCWD (FAO56-PM); n – sample size.

Results of the study. A comprehensive assessment of meteorological data obtained from the Visual Crossing Weather Data (VCWD) virtual weather station for the conditions of Polissya of Ukraine, which are necessary for the calculation of ETo, was carried out in previous studies [18].

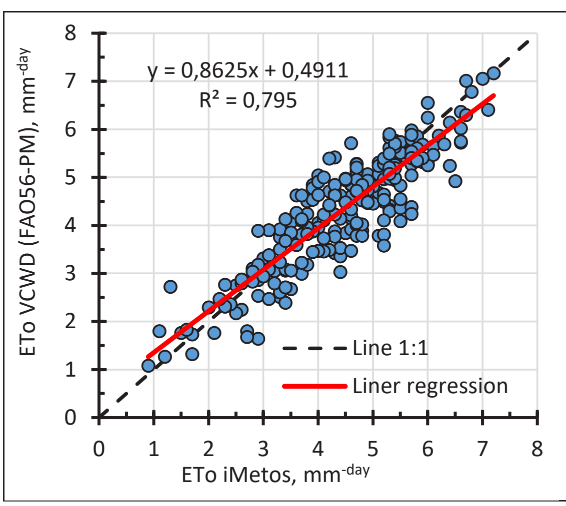
The analysis of the calculation of the reference evapotranspiration by the Penman-Monteith method (FAO56-PM) using meteorological data from Visual Crossing Weather Data indicates that the result obtained is of good accuracy. Thus, when using meteorological data from VCWD (Fig. 1a), the calculation accuracy is 86,1 %, and the RMSE and SEE errors are 0,76 and 0,49 mm, respectively (Table 1). The calculation of ETo taking into account the correction factors for meteorological data (Fig. 1b), which we obtained earlier, increases the accuracy of ETo calculations by 1,4 %, and the RMSE error decreased by 0.08 mm. The SEE error, on the contrary, increased by 0,10 mm. The most accurate calculations were obtained using the correction factor to the calculated ETo according to VCWD meteorological data, which is 1,1 (Fig. 1c). Thus, taking into account the correction factor, the accuracy of determining the ETo is 88,9 %, and the RMSE and SEE errors, respectively, are 0,58 and 0,54 mm. In the VWS Visual Crossing Weather Data setup menu, there



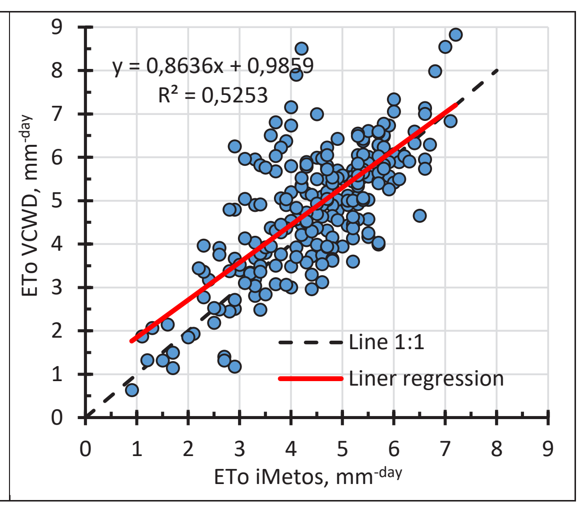
a) ETo bt VCWD meteorological data



b) ETo with correction factors to VCWD meteorological data



c) ETo according to meteorological data VCWD with a correction factor of 1.1



d) ETo by the VCWD data

Fig. 1. Regression analysis for verification of the calculated ETo by the Penman-Monteith method using VCWD meteorological data

1. MAPE, RMSE, and SEE for the calculated ETo (mm) using the Penman-Monteith method based on VCWD meteorological data (by observation periods)

Observation period	MAPE error				RMSE error				SEE error			
	1	2	3	4	1	2	3	4	1	2	3	4
sir	13,9	12,5	11,1	20,4	0,76	0,68	0,58	1,09	0,49	0,59	0,54	1,02
2023	14,9	14,1	10,0	13,6	0,78	0,75	0,55	0,74	0,46	0,62	0,51	0,70
2024	12,9	10,9	12,2	27,2	0,74	0,60	0,60	1,35	0,50	0,54	0,55	1,19
May	14,5	13,6	9,3	12,1	0,83	0,82	0,58	0,74	0,52	0,69	0,57	0,58
June	16,2	15,6	11,8	11,9	0,87	0,80	0,62	0,64	0,51	0,66	0,56	0,61
July	15,2	13,5	11,0	14,5	0,88	0,74	0,63	0,84	0,51	0,65	0,56	0,86
August	11,2	9,4	9,0	20,0	0,66	0,57	0,52	1,09	0,46	0,55	0,50	0,90
September	12,6	10,7	14,0	43,9	0,48	0,44	0,52	1,78	0,31	0,34	0,34	0,64

1 – ETo according to VCWD meteorological data; 2 – ETo with correction factors for VCWD meteorological data; 3 – ETo according to VCWD meteorological data with correction factor 1,1; 4 – ETo according to VCWD data.

is a paid option for calculating ETo, which costs $150 per month. The verification of ETo data obtained from VCWD and actual data (Fig. 1d) showed a satisfactory accuracy of the result. The errors of MARE, RMSE, and SEE were the largest and equaled to 20,4 %, 1,09, and 1,02 mm, respectively (Table 1).

For the study period of 2023-2024, the errors of MAPE, RMSE, and SEE for ETo calculated from VCWD meteorological data, taking into account the correction factor of 1,1, were 10,0–12,2 %, 0,55–0,60, and 0,51–0,55 mm, respectively. In terms of months of research, the errors of MAPE, RMSE, and SEE for this variant were in the range of 9,0–14,0 %, 0,52–0,63, and 0,34–0,56 mm, respectively.

The calculation of the absolute errors in determining ETo also confirms that the most reliable reference evapotranspiration data are obtained using a correction factor of 1,1 to ETo, which was determined from VCWD meteorological data. Thus, this variant resulted in the smallest average absolute error over the years of research, which is 5 mm. In 2024, this error was 0 (Table 2). In terms of months, the smallest absolute error of 2 mm was in May and August, and the largest was 13 mm in September.

When calculating ETo from VCWD meteorological data, the average absolute error over the years of research was 66 mm, and the use of correction factors for VCWD meteorological data in the calculations reduces the absolute error by 22 mm. In 2023 and 2024, the total ETo obtained from VCWD was 662 and 747 mm, respectively, which is 31 and 70 mm more than the actual values obtained from AWS iMetos (Table 2).

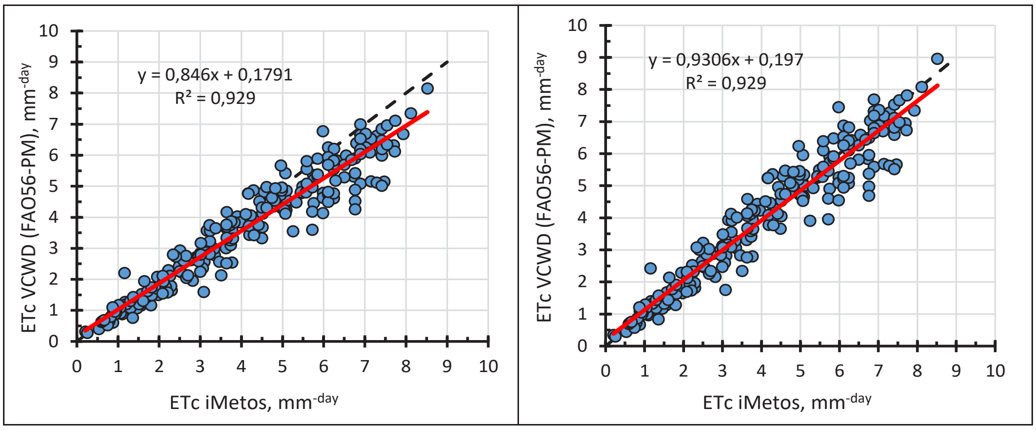
According to the results of calculations of evapotranspiration (ETc) of crops, it was found that the use of a correction factor of 1,1 to the calculated ETo increases the accuracy of ETc

2. Absolute errors of ETo, mm (by observation periods)

Observation period	Total ET_O, mm					Absolute error			
	iMetos	1	2	3	4	1	2	3	4
average	654	588	610	649	705	66	44	5	−51
2023	631	564	575	622	662	67	56	9	−31
2024	677	613	645	677	747	64	32	0	−70
May	129	114	121	128	133	15	8	2	−4
June	142	122	128	134	138	20	14	8	4
July	158	137	146	151	157	21	12	7	1
August	137	123	131	135	154	14	6	2	−17
September	88	92	84	101	123	−4	4	−13	−35

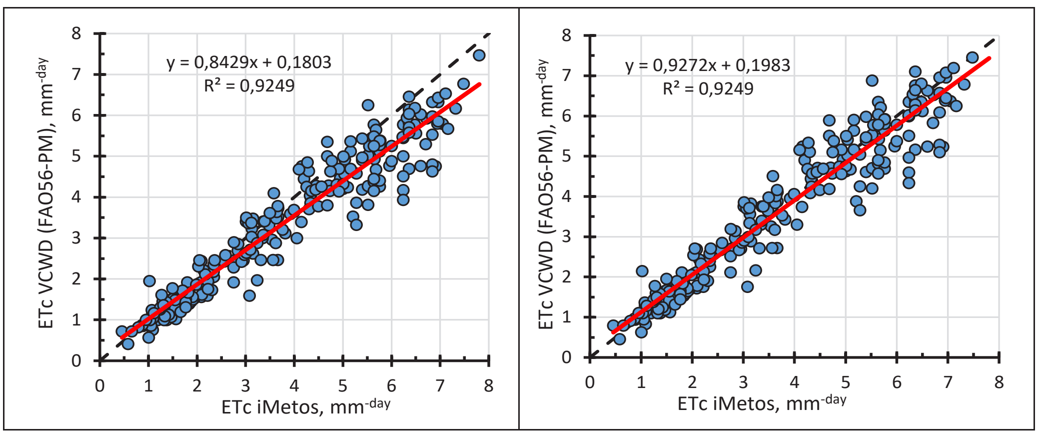
1 – ETo according to VCWD meteorological data; 2 – ETo with correction factors for VCWD meteorological data; 3 – ETo according to VCWD meteorological data with correction factor 1.1; 4 – ETo according to VCWD data.

calculations (Fig. 2–4, Table 3–4). Thus, the MAPE error decreased by 2,1 % for all crops. The RMSE errors for corn, potatoes and highbush blueberry decreased by 0,16, 0,15 and 0,09 mm, respectively. The SEE error, on the contrary, increased by 0,02–0,05 mm depending on the crop.



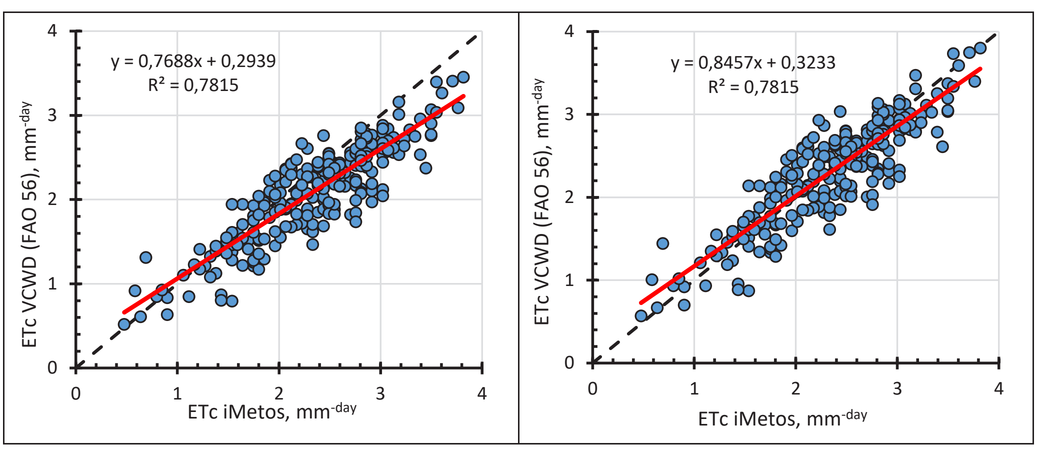
a) ETc= ETo-Ks б) ETc=1.1ETo-Ks

Fig. 2. Regression analysis for verification of the calculated seed corn ETc by the Penman – Monteith method



a) ETc= ETo-Ks б) ETc=1.1ETo-Ks

Figure 3. Regression analysis to verify the calculated ETc of potatoes by the Penman – Monteith method



a) ETc= ETo-Ks б) ETc=1.1ETo-Ks

Fig. 4. Regression analysis to verify the calculated ETc of highbush blueberry by the Penman – Monteith method

3. MAPE, RMSE and SEE for the calculated ETc (mm) by the Penman – Monteith method (by observation periods)

Observation period	MAPE error			RMSE error			SEE error		
	Corn	Potatoes	Highbush blueberry	Corn	Potatoes	Highbush blueberry	Corn	Potatoes	Highbush blueberry
average	13,7	13,7	13,7	0,74	0,69	0,40	0,50	0,47	0,27
2023 р.	14,2	14,2	14,2	0,73	0,69	0,40	0,46	0,43	0,25
2024 р.	13,1	13,1	13,1	0,76	0,70	0,39	0,54	0,50	0,27
May	14,2	14,2	14,2	0,28	0,29	0,44	0,16	0,18	0,28
June	16,1	16,1	16,1	0,65	0,61	0,46	0,37	0,35	0,27
July	15,0	15,0	15,0	1,07	0,99	0,46	0,61	0,56	0,27
August	10,5	10,5	10,5	0,75	0,69	0,33	0,54	0,49	0,25
September	12,7	12,7	12,7	0,24	0,24	0,25	0,17	0,16	0,17

4. MAPE, RMSE and SEE for the calculated ETs (mm), taking into account the correction factor of 1,1 by the Penman-Monteith method (by observation periods)

Observation period	MAPE error			RMSE error			SEE error		
	Corn	Potatoes	Highbush blueberry	Corn	Potatoes	Highbush blueberry	Corn	Potatoes	Highbush blueberry
average	11,6	11,6	11,6	0,58	0,54	0,31	0,55	0,52	0,29
2023	9,8	9,8	9,8	0,53	0,50	0,29	0,50	0,47	0,27
2024	13,3	13,3	13,3	0,62	0,58	0,33	0,59	0,55	0,30
May	9,3	9,3	9,3	0,17	0,20	0,31	0,17	0,20	0,30
June	11,8	11,8	11,8	0,47	0,45	0,33	0,41	0,39	0,30
July	11,0	11,0	11,0	0,77	0,71	0,33	0,67	0,62	0,30
August	9,5	9,5	9,5	0,64	0,59	0,28	0,59	0,54	0,27
September	16,0	16,0	16,0	0,36	0,34	0,30	0,19	0,18	0,19

The average absolute errors of ETc for the years of research using a correction factor of 1.1 to the calculated ETo for corn, potatoes and blueberries were 15,7 and 11 mm, respectively (Table 5). In May, June, and July, the calculated ETc for corn was 11, 6, and 8 mm less than the actual values, and in August and September, respectively, it was 1 and 9 mm more. This trend in the distribution of errors is also observed for potatoes and blueberries. According to the results of the research, the actual evapotranspiration of corn, potatoes and highbush blueberry in 2023–2024 was 514–535 mm, 443–472 mm and 310–345 mm, respectively. The obtained results confirm the high accuracy of determining ETc by the Penman-Monteith method using adapted crop coefficients and using the calculated ETo according to the data of the Visual Crossing Weather Data virtual meteorological station

5. Absolute errors of ETs, mm, taking into account the correction factor of 1,1 (by observation periods)

Observation period	ETc iMetos			ETc 1,1ETo VCWD (FAO56-PM)			Absolute error		
	Corn	Potatoes	Highbush blueberry	Corn	Potatoes	Highbush blueberry	Corn	Potatoes	Highbush blueberry
average	535	472	332	520	465	321	15	7	11
2023	527	452	314	508	447	302	19	5	12
2024	543	491	350	531	483	341	12	8	10
May	45	51	59	34	47	47	11	4	12
June	97	98	75	92	91	71	6	7	4
July	190	167	83	182	160	80	8	7	3
August	152	121	72	153	125	73	−1	−4	0
September	50	35	42	59	42	50	−9	−7	−8

Conclusions.

1. The results of the research confirmed the possibility of calculating ETo and ETc using the data of the virtual meteorological station Visual Crossing Weather Data.

2. To improve the accuracy of ETo calculation in the Polissya region of Ukraine, it is necessary to use a correction factor of 1,1. Taking into account the correction factor, the accuracy of determining ETo is the highest and amounts to 88,9 %, and the RMSE and SEE errors are the smallest and equaled to 0,58 and 0,54 mm, respectively.

3. According to the results of the verification, the ETo obtained from the VCWD and the actual one showed its satisfactory accuracy, which was 79,6 %, and the RMSE and SEE errors were the highest and amounted to 1,09 and 1,02 mm, respectively.

4. It was found that the use of a correction factor of 1,1 to the calculated ETo increases the accuracy of ETc calculations. Thus, the MAPE errors are reduced by 2,1 % for all crops, and the RMSE errors for corn at seeds, potatoes, and highbush blueberry are reduced by 0,16, 0,15, and 0,09 mm, respectively.

5. It was found that the average absolute errors of ETc over the years of research using a correction factor of 1,1 to the calculated ETo for corn for seed, potatoes, and blueberries were 15, 7 and 11 mm, respectively.

6. The obtained results confirm the high accuracy of determining ETc by the Penman-Monteith method using adapted crop coefficients and using the calculated ETo from the data of the Visual Crossing Weather Data virtual meteorological station

References

1. Pereira, L.S., Paredes, P., Hunsaker, D.J., López-Urrea, R., & Shad, Z.M. (2021). Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. *Agricultural Water Management*, 243, 106466. DOI: https://doi.org/10.1016/j.agwat.2020.106466

2. Allen, R.G., Dhungel, R., Dhungana, B., Huntington, Ju., Kilic A., & Morton, Ch. (2021). Conditioning point and gridded weather data under aridity conditions for calculation of reference evapotranspiration. *Agricultural Water Management*, 245, 106531. DOI: https://doi.org/10.1016/j.agwat.2020.106531

3. Veysi, Sh., Nouri, M., & Jabbari, A. (2024). Reference evapotranspiration estimation using reanalysis and WaPOR products in dryland croplands. *Heliyon*, 10, e26531. DOI: https://doi.org/10.1016/j.heliyon.2024.e26531

4. Rodrigues, G.C., & Braga, R.P. (2021). Estimation of Daily Reference Evapotranspiration from NASA POWER Reanalysis Products in a Hot Summer Mediterranean Climate. *Agronomy*, 11, 2077. DOI: https://doi.org/10.3390/agronomy11102077

5. Paredes, P., Trigo, I., de Bruin, H., Simões, N., & Pereira, L.S. (2021). Daily grass reference evapotranspiration with Meteosat Second Generation shortwave radiation and reference ET products. *Agricultural Water Management*, 248, 106543. DOI: https://doi.org/10.1016/j.agwat.2020.106543

6. Blankenau, P.A., Kilic, A., & Allen, R. (2020). An evaluation of gridded weather data sets for the purpose of estimating reference evapotranspiration in the United States. *Agricultural Water Management*, 242, 106376. DOI: https://doi.org/10.1016/j.agwat.2020.106376

7. Paredes, P., Pereira, L.S., Almorox, J., & Darouich, H. (2020). Reference grass evapotranspiration with reduced data sets: Parameterization of the FAO Penman-Monteith temperature approach and the Hargeaves-Samani equation using local climatic variables. *Agricultural Water Management*, 240, 106210. DOI: https://doi.org/10.1016/j.agwat.2020.106210

8. Faramiñan, A., Rodriguez, P.R., Carmona, F., Holzman, M., Rivas, R., & Mancino, Ch. (2022). Estimation of actual evapotranspiration in barley crop through a generalized linear model. *MethodsX*, 9, 101665. DOI: https://doi.org/10.1016/j.mex.2022.101665

9. Pareeth, S.. & Karimi, P. (2023). Evapotranspiration estimation using Surface Energy Balance Model and medium resolution satellite data: An operational approach for continuous monitoring. *Scientific Reports*, 13, 12026. DOI: https://doi.org/10.1038/s41598-023-38563-2

10. Vázquez-Rodríguez, B.A., Ontiveros-Capurata, R.E., González-Sánchez, A., & Ruíz-Álvarez, O. (2024). Comparative analysis of actual evapotranspiration values estimated by METRIC model using LOCAL data and EEFlux for an irrigated area in Northern Sinaloa, Mexico. *Heliyon*, 10, e34767. DOI: https://doi.org/10.1016/j.heliyon.2024.e34767

11. Visual Crossing Weather Data. Historical Weather Data & Weather Forecast Data. (2025). Retrieved from: https://www.visualcrossing.com

12. FieldClimate – Metos® by Pessl instrument. (2025). Retrieved from: https://ng.fieldclimate.com

13. Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrig. Drain. Paper No. 56, Rome: FAO. Retrieved from: http://www.fao.org/3/x0490e/x0490e00.htm

14. Roberts, A. (2023). Mean Absolute Percentage Error (MAPE): What You Need To Know. Retrieved from: https://arize.com/blog-course/mean-absolute-percentage-error-mape-what-you-need-to-know/.

15. Lewis, C.D. (1982). Industrial and business forecasting methods. London: Butterworths. P. 144.

16. Olumide, S. (2023). Root Mean Square Error (RMSE) In AI: What You Need To Know. Retrieved from: https://arize.com/blog-course/root-mean-square-error-rmse-what-you-need-to-know/.

17. Watts, V. (2022). Introduction to Statistics. An Excel-Based Approach. London, Ontario: Fanshawe College Pressbooks. P. 916. Retrieved from: https://ecampusontario.pressbooks.pub/introstats/

18. Zhuravlov, O.V., Shatkovskyi, A.P., Cherevychnyi, Y.O., Shcherbatiuk M.V., & Liubitskyi, V.V. (2024). Assessment of the accuracy of meteorological data obtained from virtual and automatic weather stations for the conditions of Ukrainian Polissya. *Land reclamation and water management*, 2 (120), 87–98. DOI: https://doi.org/10.31073/mivg202402-396

УДК 631.67

ОЦІНКА ТОЧНОСТІ РОЗРАХУНКУ ЕТАЛОННОЇ ТА ФАКТИЧНОЇ ЕВАПОТРАНСПІРАЦІЇ ЗА ДАНИМИ ВІРТУАЛЬНОЇ МЕТЕОСТАНЦІЇ ДЛЯ УМОВ ПОЛІССЯ УКРАЇНИ

О.В. Журавльов[1], докт. с.-г. наук, А.П. Шатковський[2], докт. с.-г. наук, М.В. Щербатюк[3], В.В. Любіцький[4], В.В. Каруна[5]

[1] Інститут водних проблем і меліорації НААН, м. Київ, 03022, Україна;
https://orcid.org/0000-0001-7035-219X ; e-mail: zhuravlov_olexandr@ukr.net
[2] Інститут водних проблем і меліорації НААН, м. Київ, 03022, Україна;
https://orcid.org/0000-0002-4366-0397 ; e-mail: andriy-1804@ukr.net
[3] Інститут водних проблем і меліорації НААН, м. Київ, 03022, Україна;
https://orcid.org/0009-0009-1784-6639; e-mail: sherbatuykmaksim@gmail.com;
[4] Інститут водних проблем і меліорації НААН, м. Київ, 03022, Україна;
https://orcid.org/0009-0000-2412-1454; e-mail: v.liubitskyi@agro-fk.com.ua;
[5] Інститут водних проблем і меліорації НААН, м. Київ, 03022, Україна;
https://orcid.org/0009-0005-6162-5391 ; e-mail: karuna@ukr.net

Анотація. *У статті проведено оцінку точності розрахунку еталонної та фактичної евапотранспірації за даними віртуальної Visual Crossing Weather Data (VCWD) та автоматичної (iMetos Base) метеорологічної станції для умов Полісся України. За результатами досліджень підтверджено можливість розрахунку ETo та ETc з використанням метеорологічних даних VCWD, точність розрахунку ETo становить 86,1 %, а похибки RMSE та SEE відповідно становлять 0,76 та 0,49 мм. Розрахунок ETo з урахуванням поправочних коефіцієнтів до метеорологічних даних підвищує точність розрахунків ETo на 1,4 %, а похибка RMSE зменшується на 0,08 мм. Найбільш точні розрахунки отримуються з використанням поправочного коефіцієнту 1,1 до обчисленої ETo. З урахуванням поправочного коефіцієнту точність визначення ETo становить 88,9 %, а похибки RMSE та SEE відповідно становлять 0,58 та 0,54 мм. Дані ETo з VCWD отримано із задовільною точністю, а похибки MAPE, RMSE та SEE були найбільшими і відповідно становили 20,4 %, 1,09 та 1,02 мм. За 2023–2024 рр. досліджень похибки MAPE, RMSE та SEE для ETo розрахованої за метеорологічними даними VCWD з урахуванням поправочного коефіцієнту 1,1 відповідно становили 10,0–12,2 %, 0,55-0,60 та 0,51–0,55 мм. В розрізі місяців досліджень похибки MAPE, RMSE та SEE для цього варіанту відповідно знаходились в межах 9,0-14,0 %, 0,52–0,63 та 0,34–0,56 мм. Розрахунок абсолютних похибок визначення ETo підтверджує, що найбільш достовірні дані еталонної евапотранспірації отримуються з використанням поправочного коефіцієнту. За цього варіанту було отримано найменшу середню абсолютну похибку за роками досліджень, яка дорвнює 5 мм,а у 2024 році ця похибка дорівнювала 0. В розрізі місяців найменша абсолютна похибка 2 мм спостерігалась у травні та серпні, а найбільша -13 мм у вересні.*

За результатами розрахунків фактичної евапотранспірації (ETc) сільськогосподарських культур встановлено, що використання поправочного коефіцієнту 1,1 до ETo підвищує точність розрахунків ETc. Похибка MAPE знизилась на 2,1 % для всіх культур, а похибка RMSE для кукурудзи на насіння, картоплі та лохини щиткової відповідно знизились на 0,16, 0,15 та 0,09 мм.

Середні абсолютні похибки ETc за роками досліджень з використанням поправочного коефіцієнту 1,1 до ETo для кукурудзи на насіння, картоплі та лохини щиткової відповідно становили 15, 7, 11 мм. В травні, червні та липні розрахована ETc для кукурудзи на насіння відповідно на 11, 6 та 8 мм менше за фактичні значення, а в серпні та вересні відповідно на 1 та 9 мм більше. Така тенденція розподілу похибок спостерігається і для картоплі та лохини щиткової.

Ключові слова: *віртуальна метеостанція, еталонна евапотранспірація, фактична евапотранспірація, кукурудза, картопля, лохина щиткова, точність, похибки MAPE, похибки RMSE та похибки SEE*

DOI: https://doi.org/10.31073/mivg202501-413
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/413

UDC: 633.15:632(477.72)

APPLICATION OF PLANT GROWTH REGULATORS ON CORN CROPS IN THE SOUTHERN STEPPE OF UKRAINE

P.V. Pysarenko[1], Dr. of Agricultural Sciences, S.O. Zaiets[2], Dr. of Agricultural Sciences, R.M. Vasylenko[3], Ph.D. in Agricultural Sciences, Z.V. Shcherbyna[4], Ph.D. in Agricultural Sciences

[1] Institute of Water Problems and Land Reclamation, NAAS, Kyiv, Ukraine;
https://orcid.org/0000-0002-2104-2301; e-mail: Pavel_Pisarenko74@ukr.net;
[2] Institute of Climate-Oriented Agriculture, NAAS, Odesa, Ukraine;
http://orcid.org/0000-0001-7853-7922; e-mail: szaiets58@gmail.com;
[3] Institute of Climate-Oriented Agriculture, NAAS, Odesa, Ukraine;
https://orcid.org/0009-0000-1903-4444; e-mail: ruslan-18a@ukr.net;
[4] Breeding and Genetics Institute – National Center for Seed Science and Variety Research, NAAS, Odesa, Ukraine;
https://orcid.org/0000-0002-4630-8372; e-mail: zoyasgi09@ukr.net

Abstract. *The aim of the research was to determine the productivity of the Ingulsky corn hybrid of the medium-ripening group of maturity depending on seed and plant treatment during the growing season when applying Regoplant and Vermystym biostimulants, as well as the effect of a plant density in different moisture conditions. Methods. The field laboratory and mathematical and statistical methods were used in the course of the research. Results. Irrigation provided an increase in the yield of silage mass by 1,4–2,2 times. Thus, on average, over three years, the highest productivity of corn for silage was observed when having a plant density of 90 thousand/ha without applying biostimulants – 48,6 t/ha and with applying biostimulants – 59,3–64,7 t/ha. The highest dry matter yield of 17,3–18,5 t/ha, feed unit yield of 16,1–17,4 t/ha and digestible protein content of 0,75–0,82 t/ha was obtained when biostimulants were applied when having a plant density of 90 thousand/ha. It was found that in non-irrigated conditions, the highest grain yield was 3,1–4,7 t/ha on the variant with a plant density of 30 thousand/ha. Applying Regoplant biostimulant provided an increase in grain yield by 1,6 t/ha, while applying Vermystym biostimulant provided an increase in grain yield by 1,2 t/ha, respectively. Conclusions. In non-irrigated conditions, it is necessary to apply Vermystym biostimulant with a sowing rate of 70 thousand/ha to obtain the highest yield of fodder units of 9,6 t/ha and 0,42 t/ha of digestible protein content from corn green mass. In irrigated conditions, the seeding rate should be increased to 90 thousand/ha and Regoplant biostimulant should be used to obtain the highest yield of feed units of 17,4 t/ha and 0,87 t/ha of digestible protein content. The cultivation of the Ingulsky hybrid corn for grain in non-irrigated conditions provided the highest yield of 4,7 t/ha with a plant density of 30 thousand/ha and applying Regoplant biostimulant. In irrigated conditions increasing a plant density to 70 thousand/ha and applying Regoplant biostimulant provided the maximum yield of 11,2 t/ha.*

Key words: *corn, biostimulants, plant density, irrigation, fertilization, productivity*

Relevance of the research.. Corn is one of the most valuable fodder crops, which provides livestock with juicy fodder (green mass, silage) and valuable fodder grain. The highest quality silage is obtained when it is mowed for vegetative mass in the phase of milk-wax and waxy grain ripeness. The nutritional value of 1 kg of green mass during these periods is 0,22–0,26 and 0,27–0,32 feed units, respectively. One kilogram of corn grain is equivalent to 1,34 feed units, while 1 kilogram of barley is equivalent to 1,26 feed units, rye – to 1,18, and oats – to 1.0 feed units. It contains 65–70 % carbohydrates, 9–12 % protein, 4–8 % fat and a small amount of fiber [1, 3, 10].

The average grain yield reaches 6-7 t/ha, although the potential productivity is much higher. When using high-yielding hybrids, moisture supply and modern growing technologies, grain yield can reach 10–12 t/ha [4, 8, 10, 24, 25].

An insufficient yield of this crop is also observed in the southern region of the country. In this regard, it is important to realize the genetic potential of modern corn hybrids through the use of irrigation, fertilizers and plant growth bioregulators in improved cultivation technologies, which create more optimal conditions for their growth and development, increase resistance to adverse environmental factors, increase yield and improve the quality of the grown products.

However, the effect of growth bioregulators on the forage productivity of new hybrids of grain-forage corn in the modern conditions of the southern region has not been sufficiently studied yet, which proves the relevance of research.

Analysis of recent research and publications. An important condition for obtaining high productivity of corn is the use of a set of optimal agrotechnical measures in view of the characteristics of the soil and climatic cultivation zone, where the sowing density plays an important role. Researchers point to its lower effect on the formation of aboveground mass under irrigation compared to the effect of mineral fertilizers [2, 5]. With insufficient moisture supply, the advantages of thickened crops decrease [7].

Treatment with growth bioregulators leads to an increase in plant height, leaf surface area of crops, accumulation of fresh mass and dry matter. With improved moisture supply under irrigation, the effectiveness of the use of growth bioregulators increases due to synergy and optimization of plant production processes [2, 12, 14].

In the conditions of Polissya, when using Biogran and Polymyxobacterin preparations for corn, an increase in crop yield of up to 20 % was recorded over a ten-year period. The effective action of biological preparations on crop productivity without deterioration of product quality in field conditions is 85–90 % [1].

In the conditions of the northern Steppe of Ukraine, the treatment of corn seeds with chelate-based biological preparations contributed to the enhanced growth intensity in the initial stage and increased grain yield. The highest effectiveness was obtained when using the complex microbial preparation Biogran, the complexes of trace elements Reastim-humus, and Reakom-S corn. The effectiveness of the preparations was determined by the background of mineral nutrition [17].

The study the effectiveness of the use of Biogran biopreparations for corn (green mass) in the system of biological and organo-mineral farming in the conditions of the Volyn RS of the Institute of Western Polissya Agriculture of NAAS on drained sod-podzolic soils, revealed that using Biogran biopreparations increases the content of nitrogen compounds in the soil by 4–14 % under the organo-mineral fertilization system. The use of Biogran and Microhumin preparations against the background of different fertilization systems increased in the yield of grain-forage crops: corn for green mass by 6,3 t/ha and spring barley – by 0,4 t/ha, compared to the control [13].

Treatment of seeds and plants in the 3–5 or 7–9 leaf phase with the microbial Polimilxobacterin preparation increases crop yield by 2.4 t/ha, protein content in grain by 0,6–1,4 % and starch by 7,9–8,9 %. With the combined use of seed bacterization and plant treatment during the growing season, the number of grains, corn cob length and thousand-grain weight significantly increase by 11 % [19, 20].

Plant growth bioregulators reveal the genetic potential of new morphobiotypes, increasing the efficiency of irrigation, which in turn contributes to increasing the profitability of their use [9, 15]. The use of growth bioregulators is especially important in crops of self-pollinated corn lines, which are characterized by low germination energy, weak initial growth, and sensitivity to damage by pests and phytoinfections [3, 8, 9].

It was established that the use of plant growth bioregulators and micronutrients improves nutrient absorption, enhances photosynthesis processes, increases plant resistance to high and low temperatures, lack of moisture, phytotoxic effects of pesticides, and damage by diseases and pests, increases yield, and contributes to the maximum use of plants' potential [6, 15, 16, 18, 23].

In the southern region of the country, the use of plant growth bioregulators "Grainactiv-S" and "Sizam-Nano" reduced the use of chemicals and increased plant resistance to adverse environmental factors under irrigation. Growing mid-season and mid-late-season corn hybrids such as Zbruch, Kakhovsky, DN Getera, Arabat when using innovative growth stimulants and micronutrients allowed obtaining grain yields of 11,1–13,4 t/ha on irrigated dark chestnut soils of southern Ukraine [3].

Thus, scientists confirm that plant growth bioregulators and micronutrients can take an important place in the system of improving corn grain production technology. However, the impact of new plant growth bioregulators on the feed productivity of high-yielding hybrids of grain-feed corn in modern conditions of southern Ukraine has not been sufficiently studied yet.

Research objectives and methodology. The purpose of the research was to substantiate theoretical provisions and improve existing technologies for growing corn by increasing its productivity under irrigation and non-irrigation conditions when using a complex of agrotechnical measures. To achieve these goals, it was necessary to investigate the productivity of a mid-ripening corn hybrid when treating seeds and plants during vegetation with plant growth bioregulators, as well as the effect of stand density under different moisture supply conditions. Field and laboratory studies were conducted according to the research methods in 2016-2018 on irrigated lands of the Institute of Climate-Oriented Agriculture of the NAAS of Ukraine [11, 21, 22].

Soils are dark chestnut, slightly saline, medium loamy with a humus layer of 45–50 cm. The humus content in the arable soil layer (0-30 cm) is 2,8–3,4 %, hydrolyzed nitrogen content is 4,5–5,5 %, mobile phosphorus content is 4,0–6,0 mg per 100 g of soil, exchangeable potassium content is 40 mg per 100 g of soil. The minimum moisture-holding capacity in the 0-50 cm of soil layer is 23,2 %, 0–100 cm – 21,5 %, 0–150 cm – 21,3 %. The withering point is 11,4; 11,6; 11,9 % to an over-dry weight, respectively. To determine the feed value of grain, a certified analytical laboratory of the institute was used.

The agricultural technology of crop growing was generally accepted for the zone. Sowing was performed in the third decade of April. Ingulsky (FAO-350) corn hybrid was sown, on irrigated and non-irrigated areas with a seeding rate of 30, 50, 70 and 90 thousand seeds/ha. The sown area was 50 m^2, the accounting area was 20 m^2.

Crops were sown when applying mineral fertilizer N_{90} in the form of ammonium nitrate applied in the period of pre-sowing cultivation. Regoplant (seed treatment rate is 250 ml/t and plant treatment rate is 50 ml/ha) and Vermistim (seed treatment rate is 10 l/t and plant treatment rate is 8 l/ha) regulators were used. The active substance of the Regoplant regulator is a complex of biologically active compounds (polysaccharides, 15 amino acids, analogues of phytohormones of cytokinin and auxin nature), biogenic trace elements, potassium salt of alpha-naphthylacetic acid and aversectin C. The active substance of the Vermistim regulator includes such biocomponents as humates, fulvic acids, amino acids, vitamins and natural phytohormones.

Plant growth bioregulators were applied for the first time in the 5–7 leaf phase, and for the second time in the 8–10 leaf phase. On average, the total irrigation rate over three years was 3000 m^3. Irrigation was performed with a DDA-100MA sprinkler.

Weather conditions during the years of research were characterized by high temperatures and droughts in the summer. In 2016 the precipitation was 87 % for June-August period, in 2017 – 22 % and in 2018 – 101 % of the norm.

Research results. One of the tasks of optimizing the production process is to form the optimal density of corn crops. Thus, on average for 2016-2018, under non-irrigated conditions, the highest productivity of corn per silage mass was when having a plant density of 70 thousand/ha with a yield of 29,2–36,3 t/ha, dry matter content of 7,7–10,8 t/ha, yield of feed units of 7,0–9,6 t/ha, digestible protein content of 0,29–0,42 t/ha and metabolic energy of 74–104 GJ (Table 1). Under these conditions, when having a plant density of 30 thousand/ha, the yield of feed units decreased by 48–50 %, digestible protein content by 48–55 %. When having a density of 50 thousand/ha, there was a decrease in feed units by 14–22 % and in digestible protein content by 17–22 %. When having a plant stand density of 90 thousand/ha, there was a decrease in the yield of feed units by 6–21 % and in digestible protein content by 10–21 %.

Biostimulant treatment of corn seeds before sowing and plants during vegetation, under non-irrigated conditions, provided an increase in dry matter yield on average by 18–27 % depending on plant density variants, and feed units by 18–28 %.

When having a plant density of 70 thousand/ha and applying Vermystym biostimulant, the feed unit yield was 9,6 t/ha, digestible protein content – 0,42 t/ha, and metabolizable energy – 104 GJ. Regoplant biostimulant was worse by these indicators by 16 %, 7 %, and 17 %, respectively.

Irrigation provided an increase in silage yield by 1,4–2,2 times. Thus, on average over three years, the highest productivity of corn for silage under irrigation was observed when having a plant density of 90 thousand/ha without applying biostimulants was 48,6 t/ha and when applying biostimulants it was 59,3–64,7 t/ha. The highest dry matter yield of 17,3–18,5 t/ha, the feed units yield of 16,1–17,4 t/ha and digestible protein content of 0,75–0,82 t/ha were obtained when applying biostimulants having a plant density of 90 thousand/ha. Applying Regoplant biostimulant provided the highest increase in silage yield by 25 % and dry matter yield by 32 %.

The effect of different factors on the formation of corn productivity showed that moisture conditions had the most significant effect on the grain and dry matter yield (82,5 % and 44,6 %, respectively). The effect of bioregulators on grain and dry matter yield was 6,1 %, 7,0 % respectively.

Thus, the main factor affecting corn productivity, both for grain and green mass, in the conditions of the southern Steppe of Ukraine is the factor of crop water supply. The use of plant growth regulators can be considered only as an additional means of increasing crop productivity.

1. Corn productivity depending on applying bioregulators under different moisture supply conditions (average for 2016–2018)

Water supply conditions (A)	Plant density, thousand/ha (C)	Yield, t/ha		dry matter yield, t/ha	Yield		
		grain	silage mass		feed units, t/ha	digestible protein content, t/ha	metabolizable energy, GJ
Non-irrigated area	Ground fertilization N_{90} (B)						
	30	3,1	14,1	4,0	3,6	0,13	39
	50	2,9	24,3	6,6	6,0	0,24	64
	70	2,6	29,2	7,7	7,0	0,29	75
	90	2,0	24,6	6,2	5,5	0,23	60
	Ground fertilization + Regoplant (B)						
	30	4,7	16,8	4,7	4,2	0,19	45
	50	4,4	26,1	7,6	6,9	0,30	73
	70	3,4	32,6	9,0	8,1	0,39	87
	90	2,5	29,9	8,1	7,6	0,35	79
	Ground fertilization + Vermystym (B)						
	30	4,4	18,5	5,4	4,8	0,22	52
	50	4,0	27,8	8,1	7,4	0,31	78
	70	3,0	36,3	10,8	9,6	0,42	104
	90	2,4	33,7	9,2	8,3	0,39	88
Irrigated area	Ground fertilization N_{90} (B)						
	30	6,1	28,7	9,0	8,4	0,33	88
	50	8,0	40,8	10,8	9,8	0,47	104
	70	9,0	46,0	12,4	11,4	0,52	121
	90	8,5	48,6	12,6	11,4	0,54	122
	Ground fertilization + Regoplant (B)						
	30	7.2	37,4	12,7	11,3	0,55	122
	50	8.6	44,1	12,3	11,6	0,54	121
	70	11.2	57,6	16,6	15,5	0,74	164
	90	10.3	64,7	18,5	17,4	0,82	182
	Ground fertilization + Vermystym (B)						
	30	6,7	33,9	11,7	10,5	0,45	112
	50	8,4	41,9	12,9	12,1	0,55	127
	70	10,7	51,6	15,3	14,4	0,66	151
	90	9,6	59,3	17,3	16,1	0,75	170
LSD_{05}:	A	0,83	0,56	0,23			
	B	0,10	0,30	0,09			
	C	0,12	0,23	0,06			

At the time of full grain maturity, in non-irrigated conditions, the highest height of corn plants was 191–205 cm when applying Vermystym biostimulant. When having a plant density of 30 thousand pcs./ha, both the highest plant height and other economically valuable characteristics of corn grain yield are recorded (Table 2).

Thus, in non-irrigated conditions, when applying Vermystym bioregulator the increase in the grain weight per cob was 16.6–44.7 % compared to the control area. However, under irrigation, treatment of plants with Regoplant bioregulator increased economically valuable characteristics more than Vermystym (Table 3). Under these conditions, the highest plant height (248–249 cm) when treating with biostimulants was when having a plant density of 30 thousand pcs./ha. Under irrigation, economically valuable characteristics also tended to decrease with increasing a plant density of corn.

When studying the effect of growth bioregulators and plant density on the grain yield of the Ingulsky corn hybrid, it was found that in non-irrigated conditions, the variant with a plant density of 30 thousand/ha was the most productive (3,1–4,7 t/ha) (Table 1). The application of Regoplant growth bioregulator provided an increase in grain yield by1,6 t/ha (52 %), and Vermystym preparation provided an increase in grain yield by 1,2 t/ha (38 %).

2. Main economically valuable characteristics of corn hybrids for grain depending on applying bioregulators in non-irrigated conditions

Plant density, thousand pcs./ha	Plant height, cm	Corn cob length, cm	Number of grains per cob, pcs	Grain weight of 1 cob, g	Weight of 1000 grains, g
Ground fertilization N_{90}					
30	200	16,0	536	123	230.0
50	200	16,0	490	105	215.0
70	187	15,6	428	94	219.2
90	180	11,7	373	78	210.0
Ground fertilization + Regoplant					
30	203	19,0	582	166	284.7
50	198	17,4	570	149	262.0
70	191	16,2	435	96	220.0
90	185	14,4	358	76	212.0
Ground fertilization + Vermystym					
30	205	19,6	633	158	239.2
50	201	17,4	598	152	264.3
70	194	17,0	588	135	230.7
90	191	14,5	412	91	220.0
$\overline{X} \pm S_{\overline{X}}$	194 ± 5	16,2 ± 1,3	500 ± 61	119 ± 21	234 ± 15

3. Main economically valuable characteristics of corn hybrids for grain depending on applying bioregulators in irrigated conditions

Plant density, thousand pcs./ha	Plant height, cm	Corn cob length, cm	Number of grains per cob, pcs	Grain weight of 1 cob, g	Weight of 1000 grains, g
1	2	3	4	5	6
Ground fertilization N_{90}					
30	247	20,5	622	218	350.5
50	243	20,0	584	201	345.0
70	238	20,5	553	189	342.3
90	231	19,8	523	146	280.0
Ground fertilization + Regoplant					
30	249	20,5	671	250	372.3
50	247	20,0	632	230	364.5
70	245	21,4	601	204	339.0
90	241	18,9	584	172	295.0

Continuation of Table 3

1	2	3	4	5	6
Ground fertilization + Vermystym					
30	248	19,8	647	230	355.0
50	246	19,8	622	211	340.0
70	242	19,6	605	193	318.8
90	240	17,9	526	152	288.0
$\overline{X} \pm S_{\overline{X}}$	243±3,2	19,9±0,5	597,5±2,2	200±20	332±19

Improving the soil fertility for corn cultivation for grain when applying plant growth bioregulators also provided a positive impact on the water consumption coefficient (Fig. 1).

Thus, in non-irrigated conditions, the lowest water consumption coefficient of 304 m^3/t was recorded when applying Regoplant growth bioregulator with a plant density of 30 thousand pcs/ha, which increased economical use of moisture by 34,2 % compared to the control; when applying Vermystym it was by 28,0 % respectively. In irrigated conditions, the greatest moisture saving was also provided by Regoplant growth bioregulator with a water consumption coefficient of 414 m^3/t when having a plant density of 70 thousand pcs/ha (by 17,0 % less compared to the control and by 6,2 % less compared to the option when applying Vermystym growth bioregulator).

On irrigated land, the Regoplant plant growth regulator provided the largest yield increase of 1,9 t (by 21 %) with a yield of 11,2 t/ha and a plant density of 70 thousand/ha. Vermystym plant growth regulator was by 6 % less effective than Regoplant and provided the highest yield of 10,4 t/ha having the same plant density of 70 thousand/ha.

Conclusions. Thus, in non-irrigated conditions, Vermystym plant growth regulator can be used to obtain the highest yield of feed units of the corn green mass of 8,3 t/ha and 0,32 t/ha of digestible protein with a seeding rate of 70 thousand/ha. In irrigated conditions, the seeding rate should be increased to 90 thousand/ha and Regoplant plant growth regulator can be used to obtain the highest yield of feed units of 14,4 t/ha and 0,67 t/ha of digestible protein.

Growing the Ingulsky corn hybrid for grain in non-irrigated conditions provided the highest yield of 4,7 t/ha when having a plant density of 30 thousand/ha and applying Regoplant plant growth regulator. In irrigated conditions increasing the plant density to 70 thousand/ha and applying Regoplant plant growth regulator provided the maximum yield of 11,1 t/ha.

In non-irrigated conditions, the lowest water consumption coefficient of 304 m^3/t was recorded when applying Regoplant plant growth regulator when having a plant density of 30 thousand/ha. In irrigated conditions, the largest moisture saving was also provided due to applying this plant growth regulator having a water consumption coefficient of 414 m^3/t and a plant density of 70 thousand/ha.

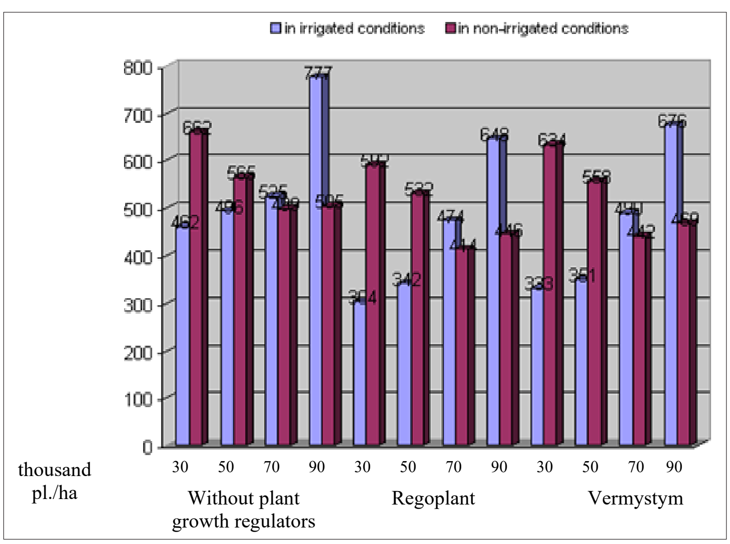


Fig. 1. Water consumption coefficient of corn for grain depending on a plant density and effect of bioregulators in different moisture supply conditions

References

1. Berdnikov, M.O., Potapenko, L.V., Skachok, L.M., & Gorbachenko, N.I. (2019). The effectiveness of microbial preparations in crop cultivation technologies in the Polissya region over the past decade. Topical issues of agricultural microbiology: materials of the All-Ukrainian scientific and practical online conference [Efektyvnist zastosuvannya mikrobnyx preparativ u texnologiyax vyroshhuvannya silskogospodarskyx kultur u zoni polissya za ostannye desyatyrichchya. *Aktualni pytannya silskogospodarskoyi mikrobiologiyi* : materialy Vseukrayinskoyi naukovo-praktychnoyi internet-konferenciyi] Chernigiv [in Ukrainian].

2. Vozhegova, R.A., & Zayets, S.O. (2022). Formuvannya adaptyvnyx texnologij vyroshhuvannya zernovyx kultur i soyi na zroshuvanyx zemlyax Pivdennogo Stepu Ukrayiny [Formation of adaptive technologies for growing cereals and soybeans on irrigated lands of the Southern Steppe of Ukraine]. Kyiv: Agrarian Science [in Ukrainian].

3. Vozhegova, R.A., Lavrynenko, Y.O., Kokovikhin, S.V., & Pysarenko, P.V. (2017). Innovacijni texnologiyi vyroshhuvannya kukurudzy na zroshuvanyx zemlyax pivdnya Ukrayiny [Innovative technologies for growing corn on irrigated lands in southern Ukraine]. Kherson: Hryn D.S. Publishing House [in Ukrainian].

4. Danilenko, Y.L. (2003). Improvement of corn cultivation technologies – the main way to increase yields [Sovershenstvovany'e texnology'j vozdeluvany'ya kukuruzu – osnovnoj put' povusheny'ya urozhajnosty']. *Corn and sorghum*, 6, 2–3 [in russian].

5. Dzyubetskyi, B.V., Pysarenko, V.A., Lavrynenko, Y.O., & Kokovikhin, S.V. (1998). Response of the mother form of hybrid Borysfen 433 MV to irrigation regime, nitrogen nutrition and plant density in hybridization plots [Reakciya materynskoyi formy gibrydu Borysfen 433 MV na rezhym zroshennya, azotne zhyvlennya ta gustotu stoyannya roslyn na dilyankax gibrydyzaciyi]. *Tavrian Scientific Bulletin*, 8, 32–34 [in Ukrainian].

6. Domaratsky, O.O. (2017). Biological products of the new generation of chelafit group in the technology of growing sunflower hybrids in the south of Ukraine [Biopreparaty' novogo pokolinnya grupy' xelafit u texnologiyi vyroshhuvannya gibrydiv sonyashnyku na pivdni Ukrayiny]. *Tavriyskyi naukovyi vistnyk*, Iss. 98, 51–56 [in Ukrainian].

7. Zolotov, V.I. (1973). Productivity and quality of corn grain depending on sowing methods, fertilizers and plant density [Produktyvnost y kachestvo zerna kukuruzы v zavysymosty ot sposobov poseva, udobrenyj y gustotu stoyanyya rastenyj]. *Bulletin of the All-Russian Research Institute of Maize*, Vol. 2, 9–12 [in russian].

8. Lavrinenko, U.O., & Zayec, S.O. (2016). Elementy tekhnolohiyi vyroshchuvannya kukurudzy na pivdni Ukrayiny [Elements of Corn Growing Technology in the South of Ukraine]. Propozytcia, 6, 58–60 [in Ukrainian].

9. Lavrinenko, U.O., & Goz, O.A. (2015). Efektyvnist stymulyatoriv rostu ta mikrodobryv na posivakh hibrydiv kukurudzy riznykh hrup styhlosti v umovakh zroshennya na pivdni Ukrayiny [Efficiency of growth stimulators and micronutrient fertilizers on hybrids of maize hybrids of different groups of ripeness in conditions of irrigation in the south of Ukraine]. *Irrigated agriculture*, 64, 15–18 [in Ukrainian].

10. Melnyk, A.V. (2013). Stan ta perspektyvy vyroshchuvannya zernovykh kultur v sviti ta Ukrayini [Status and Prospects for Growing Cereals in the World and Ukraine]. *Bulletin of the Sumy National Agrarian University*, Vol. 11 (26), 131–134 [in Ukrainian].

11. Vozhegova, R.A. (Ed.) (2014). Methods of field and laboratory research on irrigated lands [Metodyka polovyx i laboratornyx doslidzhen na zroshuvanyx zemlyax]. Kherson: Green D.S. [in Ukrainian].

12. Polishchuk, K. (2015). Efficiency of biological products in the system of biological farming on reclaimed lands of Volyn Polissya [Efektyvnist biopreparativ u systemi biologichnogo zemlerobstva na meliorovanyx zemlyax Volynskogo Polissya]. *Agricultural and resource economics: international scientific e-journal*, Vol. 1, (1), 38–47 [in Ukrainian].

13. Popova, L.V. (2015). Study of the influence of growth bioregulators on the yield of winter wheat, with different methods of their application, in the conditions of Komiternivskyi district of Odesa region [Vyvchennya vplyvu regulyatoriv rostu na urozhajnist ozymoyi pshenyci, pry riznyx sposobax yix zastosuvannya, v umovax Komiternivskogo rajonu Odeskoj oblasti.] Agrarian Bulletin of the Black Sea Region. *Agricultural sciences*, 76, 59–64 [in Ukrainian].

14. Semenyaka, I.M. (2010). Efficiency of microbial preparations, macro- and microfertilizers for the cultivation of split corn [Efektyvnist mikrobnyx preparativ, makro- ta mikrodobryv za

vyroshhuvannya rozlusnoyi kukurudzy]. *Collection of scientific papers of the National Scientific Center "Institute of Agriculture of UAAS"*, Vol. 3, 84–91 [in Ukrainian].

15. Semin, S.A. (2014). Vlyanye udobrenyj i regulyatorov rosta na produktyvnost kukuruzu [Influence of fertilisers and growth bioregulators on maize productivity]. *Scientific and Production Journal "Kormoproizvodstvo"*, 25–28 [in russian].

16. Semyashkina, A.O. (2015). Produktyvnist sortiv vivsa zalezhno vid zastosuvannya biopreparativ za riznykh pohodnykh umov [Productivity of oat varieties depending on the use of biological agents under different weather conditions]. *Irrigated agriculture*, 64, 91–95 [in Ukrainian].

17. Sidorenko, O.I., Babanin, V.V., & Morozov, O.V. (2013). Ecological and agro-meliorative monitoring of irrigated lands: a workshop [Ekologo – agromelioratyvnyj monitory'ng zroshuvanyx zemel: praktykum.] Kherson: Kolos [in Ukrainian].

18. Solonenko, S.V., & Chomin, V.Y. (2017) Vplyv rehulyatora rostu rehoplant na urozhaynist ta tekhnolohichni pokaznyky yakosti nasinnya safloru krasylnoho v umovakh Pivnichnoho Stepu Ukrayiny [Influence of the regroplant growth bioregulator on the yield and technological parameters of the quality of the safflower seed dyed in the conditions of the Northern Steppe of Ukraine]. *Taurian scientific bulletin*, 67, 15–18 [in Ukrainian].

19. Tkalich, Y.I., Tsilyuryk, O.I., & Kozechko, V.I. (2017). Optimization of microfertilizers and plant growth bioregulators application in corn crops in the Northern Steppe of Ukraine [Optymizaciya zastosuvannya mikrodobryv ta regulyatoriv rostu roslyn u posivax kukurudzy Pivnichnogo Stepu Ukrayiny]. *Bulletin of Dnipropetrovs'k State Agrarian and Economic University*, 4, 20–25 [in Ukrainian].

20. Tokmakova, L.M., & Shevchenko, L.A. (2019). The effect of Polymyxobacterin on corn productivity under different methods of application [Vplyv Polimiksobakterynu na produktyvnist kukurudzy za riznogo sposobu zastosuvannya]. *Agroecological journal*, 1, 80–84 [in Ukrainian].

21. Ushkarenko, V.O. (2014). Methodology of field experiment (irrigated agriculture) [Metody'ka pol'ovogo doslidu (zroshuvane zemlerobstvo)] Study guide. Kherson: FOP Grin D.S. [in Ukrainian].

22. Ushkarenko, V.O., Nikishenko, V.L., Goloborodko, S.P., & Kokovikhin, S.V. (2008) Analysis of variance and correlation in agriculture and plant growing [Dyspersijnyj i korelyacijnyj analiz u zemlerobstvi ta roslynnycztvi] Study guide. Kherson: Ailant [in Ukrainian].

23. Fedorchuk, S.V. (2017). Vplyv khimichnykh preparativ, biolohichnykh i rehulyatoriv rostu roslyn na rozvytok zbudnykiv altenaria solani ta phytophtora infestans [Influence of chemical preparations, biological and growth bioregulators of plants on the development of pathogens altenaria solani and phytophtora infestans]. Kherson. *Taurian scientific bulletin*, 98, 128–133 [in Ukrainian].

24. Shatkovskyi, A.P., Zhuravlev, O.V., Melnychuk, F.S., Ovchatov, I.M., & Yarosh, A.V. (2020). Influence of irrigation methods on corn productivit [Vplyv sposobiv zroshennya na produktyvnist kukurudzy]. *Crop and soil science*, 4, 34–42. DOI: https://doi.org/10.31548/arg.2020.04.034 [in Ukrainian].

25. Shatkovskyi, A.P., Zhuravlev, O.V., & Ovchatov, I.M. (2020). Irrigation regimes and water consumption of soybeans and corn depending on irrigation methods [Rezhy'my' zroshennya ta vodospozhy'vannya soyi i kukurudzy' zalezhno vid sposobiv zroshennya]. *Tavrian Scientific Bulletin*, 115, 262–229. DOI: https://doi.org/10.32851/2226-0099.2020.116.2.25 [in Ukrainian].

УДК 633.15:632(477.72)

ВПЛИВ РІСТ-РЕГУЛЮЮЧИХ ПРЕПАРАТІВ НА КОРМОВУ ПРОДУКТИВНІСТЬ КУКУРУДЗИ В УМОВАХ ПІВДНЯ УКРАЇНИ

П.В. Писаренко[1], докт. с.-г. наук, С.О. Заєць[2], докт. с.-г. наук, Р.М. Василенко[3], канд. с.-г. наук, З.В. Щербина[4] канд. с.-г. наук

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-2104-2301; e-mail: Pavel_Pisarenko74@ukr.net;
[2] Інститут кліматично орієнтованого сільського господарства НААН, Одеса, Україна;
http://orcid.org/0000-0001-7853-7922; e-mail: szaiets58@gmail.com;
[3] Інститут кліматично орієнтованого сільського господарства НААН, Одеса, Україна;
https://orcid.org/0009-0000-1903-4444; e-mail: ruslan-18a@ukr.net;
[4] Селекційно-генетичний інститут – Національний центр насіннєзнавства та сортовивчення НААН, Одеса, Україна; https://orcid.org/0000-0002-4630-8372; e-mail: zoyasgi09@ukr.net

Анотація. *Метою досліджень було визначити продуктивність гібриду кукурудзи Інгульський середньостиглої групи стиглості залежно від обробки насіння й рослин по вегетації біостимуляторами Регоплант та Вермистим, а також впливу густоти стояння за різних умов зволоження. Методи. У процесі виконання досліджень використовували польовий метод, лабораторний та математично-статистичний методи. Результати. Зрошення забезпечило збільшення врожайності силосної маси до 1,4–2,2 рази. Так, в середньому за три роки, на зрошенні найбільша продуктивність кукурудзи на силосну масу відмічалась за густоти 90 тис./га без підживлення біостимуляторами – 48,6 т/га та з підживленням біостимуляторами – 59,3–64,7 т/га. Найбільший збір сухої речовини 17,3–18,5 т/га, виходу кормових одиниць 16,1–17,4 т/га та перетравного протеїну 0,75–0,82 т/га отримано при внесенні біостимуляторів за густоти 90 тис./га. Встановлено, що за неполивних умов найбільша урожайність зерна становила 3,1–4,7 т/га на варіанті з густотою 30 тис./га. Застосування біостимулятора Регоплант забезпечило прибавку врожаю зерна на 1,6 т/га, а препарату Вермистим відповідно на 1,2 т/га. Висновки. За неполивних умов, для найбільшого виходу з зеленої маси кукурудзи кормових одиниць 9,6 т/га й 0,42 т/га перетравного протеїну необхідно застосовувати біостимулятор Вермистим з нормою висіву 70 тис./га. На зрошенні варто збільшувати норму висіву до 90 тис./га й використовувати біопрепарат Регоплант з отриманням найбільшого виходу кормових одиниць 17,4 т/га й 0,87 т/га перетравного протеїну. Вирощування гібриду кукурудзи Інгульський на зерно за неполивних умов забезпечило найбільшу врожайність 4,7 т/га із густотою стояння 30 тис./га та застосування препарату Регоплант. На зрошенні збільшення густоти стояння рослин до 70 тис./га й застосування цього ж препарату, забезпечує максимальну врожайність 11,2 т/га.*

Ключові слова: *кукурудза, біостимулятори, густота стояння, зрошення, удобрення, продуктивність*

DOI: https://doi.org/10.31073/mivg202501-412
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/412

UDC 631.62:631.432:633.2

ASSESSMENT OF THE TECHNICAL CONDITION OF THE KRASNOPAVLIVSK RESERVOIR EARTH DAM

I.V. Voytovych[1], Ph.D., Ya.V. Shevchuk[2], O.M. Kozytskyi[3], O.S. Ignatova[4], G.Ya. Boyko[5], Yu.V. Limachov [6]

[1] Institute of Water Problems and Land Reclamation of NAAS, 03022, Kyiv, Ukraine;
https://orcid.org/0000-0002-1543-3955, e-mail: ivan.v.voytovich@gmail.com;
[2] Institute of Water Problems and Land Reclamation of NAAS, 03022, Kyiv, Ukraine;
https://orcid.org/0000-0001-6718-3874; e-mail: yaroslav_shevchuk@ ukr.net;
[3] Institute of Water Problems and Land Reclamation of NAAS, 03022, Kyiv, Ukraine;
https://orcid.org/0000-0002-4459-6331, e-mail: olegkoz@ukr.net;
[4] Institute of Water Problems and Land Reclamation of NAAS, 03022, Kyiv, Ukraine;
https://orcid.org/0000-0002-2074-4555, e-mail: ignatovaoks@ukr.net;
[5] Institute of Water Problems and Land Reclamation of NAAS, 03022, Kyiv, Ukraine;
https://orcid.org/0000-0002-2710-8543, e-mail: boykoG7@gmail.com;
[6] Institute of Water Problems and Land Reclamation of NAAS, 03022, Kyiv, Ukraine;
https://orcid.org/0009-0008-5217-763X; e-mail: leman4767@gmail.com

Abstract. *Dams and weirs of the reservoirs are objects of increased man-made hazard, which is due to the high probability of catastrophic flooding of territories and destruction as a result of their breakthroughs. The probability of technogenic accidents at reservoirs increases not only with exceeding the design operating lifespan, but also as a result of hostilities and climate changes, which lead to changes in the hydrological regime of surface and groundwater. According to the conducted research, it has been found out that monolithic reinforced concrete supports of the upper slopes of dams are particularly susceptible to destruction. This is primarily due to the destruction of temperature-deformation and structural joints of fastening structures, as well as the manifestation of chemical and mechanical suffosion. As a result, cavities form in the base of the earth dam body deck, which leads to subsidence and destruction of the deck, a decrease in the stability of the upper slope, and the manifestation of filtration processes. In order to assess the technical condition of the structural elements of the earth dam of the Krasnopavlivsk reservoir and determine the potential reserve of its operation, field surveys were conducted, which allowed assessing the stability of both the fastening structures and the earth dam body. The reservoir was put into operation in 1984 as a component of the hydroelectric facility of Dnipro–Donbas canal. It ensures the uninterrupted operation of the canal, and in case of emergencies it is used as a freshwater reservoir for water supply. The reservoir dam is made of soil. The upper slope is secured in the lower part with a stone cape, and in the upper part with monolithic reinforced concrete slabs. The bottom slope is secured with a layer of soil with grass seeding. To discharge the filtration water and drain it into an open drainage collector, tubular drainage and discharge wells are arranged. The dam's load characteristics are typical for the most reservoir dams in Ukraine. During the surveys, a set of diagnostic methods was used, including non-destructive examinations of the concrete cover of the upper slope reinforcement and assessment of its strength using a Schmidt hammer, georadar studies to determine cavities in the thickness of the underlying layer of the soil dam base under the concrete cover using a VIY5 600 georadar, as well as geodetic methods for measuring the geometric parameters of facilities' structures and the consequences of the destruction of structural elements. According to the research materials, violations of the geometric parameters of the dam were noted, as well as the presence of deformation processes in the form of the subsidence of the dam crest in places where anomalous phenomena occurred. The effect of the destruction of the concrete cover on the stability of the earth dam, the manifestation of the activation of filtration processes accompanied by increased suffosion of the underlying layer of the base of the reinforcement, were noted.*

Keywords: *reinforced concrete reinforcement, earth dam, depression curve, surveys, non-destructive testing methods, suffosion, technical condition*

Relevance of research. Reservoirs play a key role in the systems of water supply, energetics, and irrigation in Ukraine.

The hydraulic facilities of reservoirs built during the 60s and 70s years of XX century require radical restoration and technical re-equipment. Among the hydraulic facilities, earth dams have a special place, as they are the most affected by wave and mechanical loads. According to previous studies, monolithic reinforced concrete supports of the upper slopes of dams are particularly susceptible to destruction.

This is primarily due to the destruction of temperature-deformation and structural joints of the fastening structures, as well as the manifestation of chemical and mechanical suffosion, which is accompanied by the formation of cavities in the base of the deck of the earth dam body, leads to the subsidence and destruction of the deck, a decrease in the stability of the upper slope, and the manifestation of filtration processes.

The determination and assessment of the technical condition of facilities, the determination of a potential reserve for their operation, is possible by conducting field surveys, which make it possible to fully assess the stability of both the supporting structures and the earth dam.

During the assessment of earth dams' technical conditions, the following are the subjects of inspection: structures for fastening the upper and lower slopes; the condition of monitoring wells for determining the filtration regime of the facility; facilities of the drainage system; the body of the earth dam.

To conduct field surveys of the technical condition of earth dam facilities, the earth dam of the Krasnopavlivsk reservoir was chosen as the base object, which is typical in terms of loads for almost the most reservoir dams.

Analysis of recent research. There are 1054 reservoirs and 49444 ponds, with a total area of 2891 km^2 [1, 2], a complex of water protection dams with a length of 3,8 thousand km, 1,2 thousand km of banks reinforcement, and over 600 pumping and compressor stations for pumping excess water that are operated in Ukraine [3]. Dams and weirs of the reservoirs are the objects of increased man-made hazard, which is due to the high probability of catastrophic flooding of territories and destruction as a result of their breakthroughs. The probability of man-made accidents at reservoirs increases not only with exceeding the design operating lifespan, but also with the consequences of hostilities, and climate changes. The latter leads to the changes in the hydrological regime of surface and groundwater. For these reasons, in Ukraine, special attention is paid to ensuring the reliability and safety of hydraulic facilities' operation, both in terms of improving the legislative regulation of the rules for their safe operation [4, 5], monitoring the hydrological regime of rivers and reservoirs, and the technical condition of facilities, determining the criteria for their stability and safety, increasing work efficiency, improving the technical base and methods of surveys, determining the causes of emergency situations, modeling and forecasting negative consequences as a result of emergency situations during the destruction of dams, levees, gates, landslide processes, etc. [6, 7]. A significant number of recent scientific studies are devoted to the current problems of assessing the technical condition and forecasting possible negative consequences of the operation of individual reservoirs, including the Krasnopavlivsk reservoir [3, 8–10]. In [10], a program for assessing the consequences of a hydrodynamic accident, developed on the example of the Krasnopavlivsk reservoir is presented.

The aim of research. Assessment of the technical condition of the structural elements of the earth dam of the Krasnopavlivsk reservoir.

Research methodology. The research was carried out in accordance with the "Methodology for conducting field surveys of earth dams and protective dams of water management purposes" developed at the Institute [11].

During the assessment of the technical condition of the earth dam of the hydroelectric facility, the following were subjects of survey: the dam body; fastening of the upper slope at levels from 106,5 to 112,0 m; fastening of the lower slope; filtration regime of the facility.

A set of diagnostic methods was used, which included:

– visual inspections of the object (photos of damages);
– non-destructive surveys of the concrete covering of the upper slope reinforcement (using a Schmidt hammer);
– georadar studies to determine cavities under concrete pavement (VIY5 600 georadar);
– instrumental measurements of geometric parameters of facilities and the consequences of destruction of structural elements (level, measuring tape, gap gauge, etc.).

The position of the depression curve was determined based on the results of groundwater level monitoring in observation wells located on the downstream slope of the dam.

Research results and their discussion. *The Krasnopavlivsk reservoir* is located in the Lozovsky district of the Kharkiv region and is an important component of the water supply system of the Donbas and the Kharkiv regions. The situational plan and general view of the Krasnopavlivsk reservoir are shown in Fig. 1. The reservoir was put into operation in 1984 as a component of the Dnipro–Donbas canal. The total volume of the reservoir is 410 million m^3, the useful volume is 380 million m^3, the length of the coastline is 127,4 km, and the greatest width is 2,48 km.

a b c

a – situational plan; b – panoramic view; c- dam crest

Fig. 1. Krasnopavlivsk reservoir

The mirror area at normal supported level (NSL) is 34 km^2, and the catchment area is 35 km^2. The reservoir is of a canal type, located in the valley of the Popilnya river. To accumulate the water coming from the Kamyansk reservoir, an earth dam of 2,2 km long and 35 m high was built in the area of the Krasnopavlivka settlement. The hydroelectric facility includes: an earth dam and a water outlet (bottom, tubular). The reservoir is characterized by seasonal flow regulation. The reservoir ensures uninterrupted operation of the canal, in the case of an accident, it is also used as a freshwater reservoir for water supply to Kharkiv, Lozova, and Pervomayisk [12].

Krasnopavlivsk Reservoir Dam. The dam is made of soil, homogeneous loam, classified as CC2. The base of the dam's canal section is made of silty loam, which is why the dam has a flattened profile.

To improve the conditions for the consolidation of the foundation soils and the drainage of the dam body, a sand cushion 0,5 m thick is provided under its bottom wedge on the left and right bank sections, and up to 1,0 m thick on the canal section of the dam.

Dam's parameters are as follows: total length – 2200 m; width along the crest – 12 m; maximum height – 35 m; crest mark – 123,5 m; maximum design level (MDL) in the upper reaches – 120,0 m; maximum reservoir filling volume – 410 million m$^{3;}$ top slope 1:3, bottom slope 1:7. A highway runs along the crest of the dam.

The upper slope up to the 100,0 m mark is secured with a stone cap D=150–250 mm, higher (to the dam crest) – with monolithic reinforced concrete slabs with a thickness from 20 cm up to 25 cm. The lower slope is secured with a layer of soil with grass seeding.

Under the lower slope of the dam, there is a tubular drainage designed to discharge filtration waters and drain them into an open drainage collector.

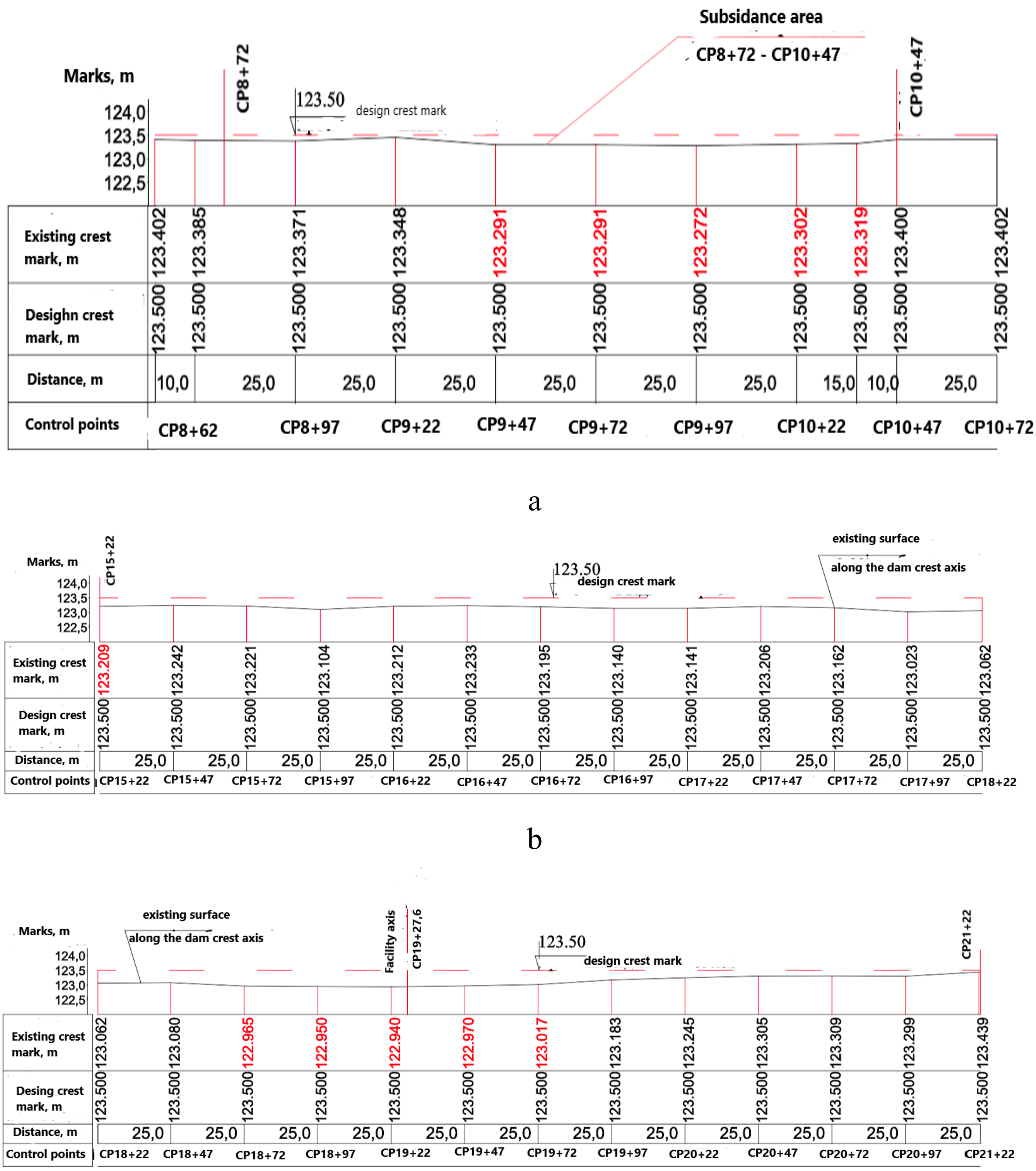
In the downstream part of the dam, unloading wells and closed drainage of the right slope of the dam are provided.

The above-mentioned engineering solutions aimed to ensure the reliability of the hydropower facilities were adopted after the tests with static and dynamic loads, especially wave loads and the tests of the impact of changes in the level regime.

Considering that the main damages of dam structures are associated with changes in the loads on the dam, including changes in the level regime of filling the reservoir and its operation, predicting the technical condition of structures is directly related to the results of monitoring and the need of conducting field surveys.

Field surveys of the dam's geometric parameters. During of the deformation processes survey of the earth dam body, subsidence along the crest was recorded. The condition of the upper slope fastening was determined by the presence of subsidence of the reinforced concrete fastening; the condition of temperature and deformation joints, the presence of cracks as a result of the destruction of the cladding, areas of destruction of the reinforced concrete fastening, the detection of cavities under the cladding as a result of chemical and mechanical suffosion and, as a result, the removal of soil particles from under its base were recorded. The results of instrumental surveys were presented in a form of a table according to the Methodology for conducting field surveys of earth dams and protective dams for water management purposes.

To assess the deformation processes occurring in the dam body, a geodetic survey was performed. According to the survey results, the subsidence of the dam crest ranged from 35 cm (CP8+22–CP11+97) to 64 cm (CP15+22–CP 21+22) (Fig. 2).



a – CP8+72 – CP10+47; b – CP15+22 – CP18+22; c – CP18+22 – CP21+22

Fig. 2. Longitudinal profiles along the axis of the dam crest in areas of subsidence

Thus, the selection of these plots for further survey is related to the nature and magnitude of subsidence, which became the basis for further research in terms of geophysical diagnostics of the technical condition of the upper slope at elevations 106,5–112,0 m at the indicated plots. The layout of the cross-section bases during the diagnostics of the earth dam body along with the results of visual inspection and vibroacoustic diagnostics on CP8-CP8+50 are shown in Fig. 3, 4. In Fig. 4, the area of cavity formation under the concrete coating is marked in red.

Geophysical studies to determine anomalous processes along the underlying layer of the earth dam's concrete foundation were performed using the VIY5 600 Georadar instrument at CP8-CP8+50. The probing depth can reach up to 3,5 meters.

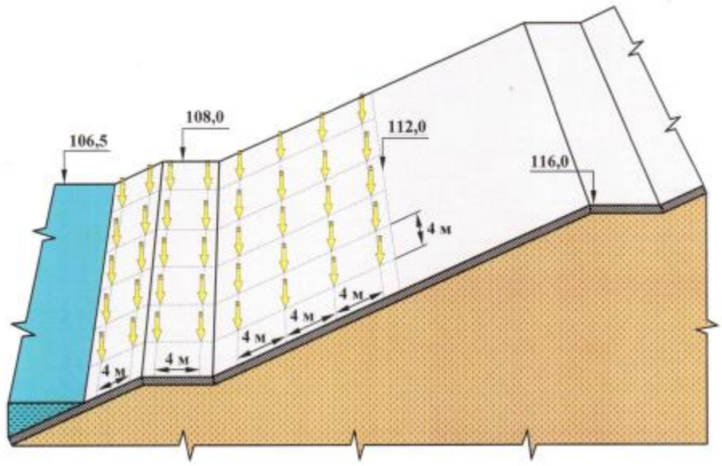


Fig. 3. Layout of cross-section bases during diagnostics of the earth dam body

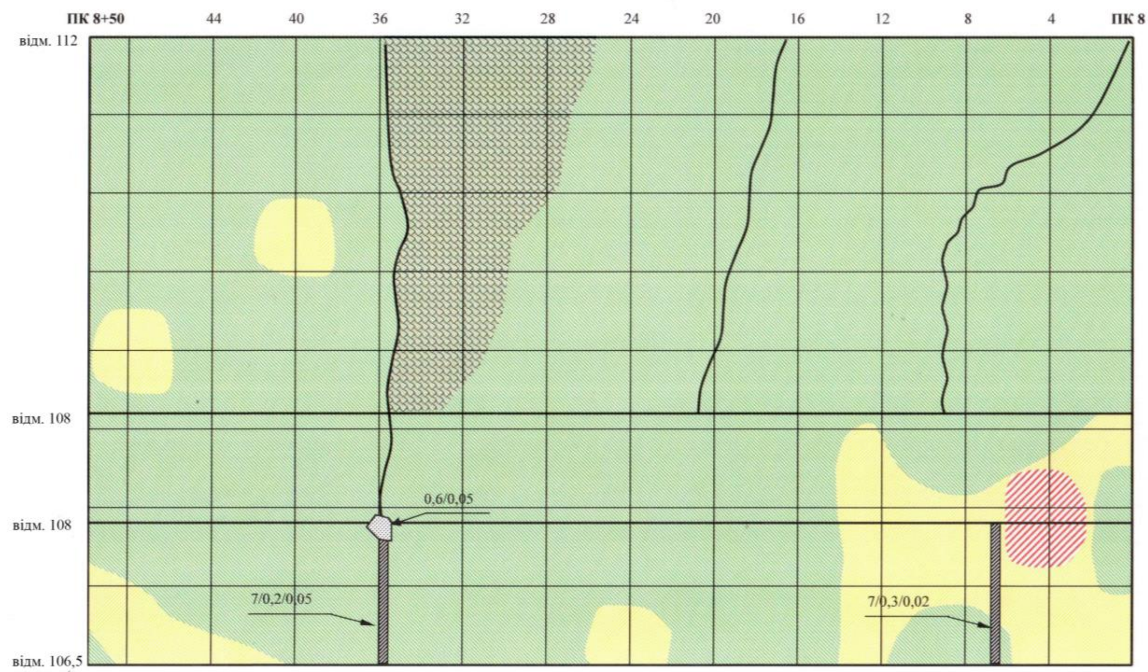


Fig. 4. Results of visual inspection and vibroacoustic diagnostics on CP8-CP8+50

The formation of voids under the concrete facing of the upper slope is due to the manifestation of suffosion processes of removal of the underlying sand layer as a result of overmoistening due to the pressure filtration through deformation-temperature joints and cracks in monolithic concrete.

Based on the materials of the conducted surveys, the areas and volumes of voids under the concrete covering of the upper slope at the elevations of 106.5–112.0 m of the CP8-CP10 section, and the category of destruction were determined (Table 1).

The area of destruction according to the above-mentioned criteria is on average: “low” – 80,85 %; “medium” – 16,28 %; “high” – 11,5 %.

Taking into account the significant size of the object (the dam length is 2200 m), the study of the technical condition of the upper slope reinforcement at the marks 106,5–112,0 m was carried out according to the following program: visual inspections of the dam’s technical condition; assessment of the condition of local areas of destruction of the upper slope reinforcement; detailed assessment of the condition of the temperature and deformation (structural) joints; assessment of the condition of the concrete covering of the reinforcement.

1. Volumes of voids under the concrete pavement at the plot CP8-CP10

Plots	Area, m^2			Voids volume, m^3			Total volume, m^3
	Destruction category			Destruction category			
	Low	Medium	High	Low	Medium	High	
CP8-CP8+50	89,0	9,9	1,1	2,8	1,6	0,7	5,1
CP8+50-CP9	81,5	15,7	2,8	2,6	2,5	1,8	6,9
CP9-CP9+50	70,0	23,6	6,4	2,2	3,8	4,1	10,1
CP9 +50-CP10	82,9	15,9	1,2	2,7	2,5	0,8	6,0

Diagnostics of reinforced concrete facilities by a non-destructive method using mechanical devices was used to determine the actual grade of concrete in order to establish its compliance with design solutions. The work on determining the concrete grade was carried out in accordance with the current regulatory and methodological provisions [13–15].

The concrete grade was determined by a non-destructive method using a Schmidt reference hammer. The Schmidt hammer works on the principle of elastic rebound, which measures the impact impulse generated in concrete under an applied load. This method is borrowed from the practice of measuring the strength of metals.

Based on the research results, the concrete grade of individual elements of the hydraulic facilities of the Krasnopavlivsk reservoir was determined.

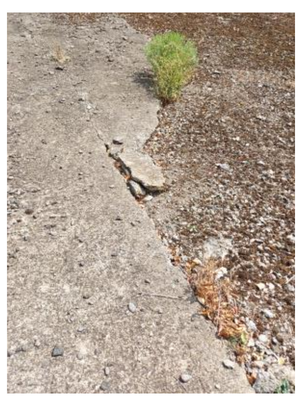
The strength of the concrete fastening of the upper slope of the dam at the control points CP8+22–CP11+97 and CP15+22–CP21+22, according to the results of the research, is as follows: in line 1 – 42,36 MPa; in line 2 – 44,28 MPa (the concrete strength of 38,54 MPa corresponds to class C25/30).

In accordance with the survey program, documentary confirmation of the detected damage to the concrete pavement was carried out by visual inspection with photo fixation and instrumental measurements (Fig. 5).


a

b

c

d

e

j

a – local destruction of expansion joints; b – formation of cracks; c – local spalling of concrete; d – destruction of structural joints; e – corrosion of the concrete surface; f – decompression of temperature-deformation joints

Fig. 5. Detected damage to the concrete covering of the upper slope of the dam

The results of the survey of the technical condition of the monolithic concrete reinforcement of the upper slope of the Krasnopavlivska dam in the zone of marks from 106,5 to 112,0 m are given in Table 2.

The presented research results provided an opportunity to assess the technical condition of monolithic concrete reinforcement and outline technical measures to eliminate the damage.

The filtration strength of the dam body was assessed based on research materials during the filtration processes observation. Special attention was paid to the position of the depression curve; the shore connections of the earth dam and the concrete part of the hydroelectric facilities; concentrated filtration in the form of fistulas, boils, springs; the presence of filtration from the base in the low part.

Based on the position of the depression curve, calculations on the filtration strength of the dam body based on pressure gradients were made.

The calculation of the effective (actual) average head gradient $J_{est.m}$ was performed using the formula [16]:

$$J_{est.m} = H/L,$$

where H is the calculated pressure difference between the upper and lower parts; L is the length between calculation points A and B according to the calculation scheme for the average head gradient (Fig. 6).

2. Destruction of monolithic concrete reinforcement of the upper slope of the Krasnopavlivska dam

№№	Survey plot		2024			
			Cracks		Seams	
	From CP	To CP	Quantity, pcs.	Total length, m	Destroyed, pcs.	Total length, m
1	2	3	7	8,0	9	10,0
2	4	6	3	72,0	2	64,0
3	6	7	2	70,8	3	112,0
4	7	8	2	47,8	2	70,0
5	8	9	2	43,0	1	32,0
6	9	10	2	59,0	2	64,0
7	10	11	1	32,0	6	192,0
8	11	12	5	110,0	2	71,0
9	12	15	2	41,0	2	64,0
10	15	17	3	90,0	–	–
11	17	18	1	27,0	–	–
12	18	19	1	27,0	1	16,0
13	19	20		–	4	55,0
14	20	22				
Total				627,6		750,0

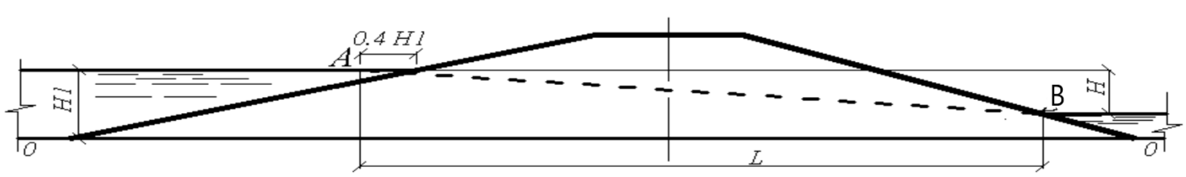


Fig. 6. Scheme for calculating the average head gradient $J_{est.m}$

The filtration strength of the earth dam was determined by calculating the average head gradient $J_{est.m}$ on three transverse lines at CP14+63; CP15+56; CP16+70.

The calculation of the theoretical depression curve was performed taking into account the mark of the lower part at the drainage gallery, which corresponds to 90,60–90,70 m [17]. As an example, Figure 7 shows the calculation diagram of the position of the depression curve along the line1 (CP14+63).

The results of calculations of the theoretical head gradient $J_{est.m}$ along the lines 1-3 are given in Table 3.

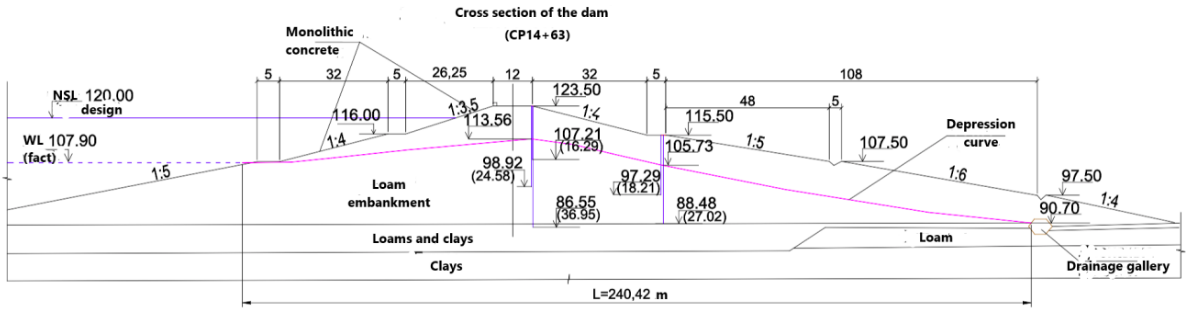


Fig. 7. Calculation scheme for determining the average pressure gradient

3. Results of the theoretical head gradient $J_{est.m}$ calculation of Krasnopavlivska earth dam

Line number	Control point	Water level in the reservoir	Average head gradient of the dam body $J_{est.m}$		Dam body soil
			theoretical	critical [6]	
Line 1	CP 14+63	107,90	0,076	1,5 – 4,0	Loam
Line 2	CP 15+56	107,90	0,07	1,5 – 4,0	Loam
Line 3	CP 16+70	107,90	0,072	1,5 – 4,0	Loam

As can be seen from Table 3, the head gradient of the earth dam as of September 8, 2024 is from 0,076 (line 1) to 0,07 (line 2) – which is significantly less than critical and indicates a safe filtration mode of the dam.

Based on the position of the depression curve, calculations of the actual pressure gradient were performed.

Since the depression curve has a positive and negative slope, calculations of the actual head gradient were performed for two components of the depression curve position (Table 4).

Table 4 presents the results of calculations on the actual position of the depression curve with positive and negative slopes.

4. Results of calculation of the actual head gradient $J_{est.m}$ of the Krasnopavlivska earth dam

Line number	Control point	Water level in the reservoir	*Average head gradient of the dam body $J_{est.m}$*			Dam body soil
			actual		critical [6]	
			with positive slope	with negative slope		
Line 1	CP 14+63	107,90	0,10	0,06	1,5–4,0	Loam
Line 2	CP 15+56	107,90	0,15	0,04	1,5–4,0	Loam
Line 3	CP 16+70	107,90	0,13	0,04	1,5–4,0	Loam

As can be seen from Table 4, the values of the head gradients of the earth dam for both positive and negative slopes of the depression curve indicate a safe filtration regime of the dam.

Conclusions

1. By instrumental studies we have determined the presence of the subsidence of the crest of the earth dam in two sections – CP8+22–CP11+97 and CP15+22–CP21+22, respectively, by 0,35 m and 0,64 m, which indicates a violation of the stability of the dam in these sections.

2. Typical destructions of reinforced concrete covering are the destruction of temperature-deformation joints as a result of a failure of wooden fillings; the presence of transverse and longitudinal cracks in the reinforced concrete covering as a result of a decrease in the stability of the fastening base, which is caused by the development of filtration processes (mechanical suffosion) and the removal of particles from the sand cushion (h = 0,35 m); the corrosion and local destruction of concrete.

3. The crack openings, the size of which reaches up to 3,0 cm, are due to the presence of deformation processes of the base of the underlying layer of concrete reinforcement, as a result of which cracks form in the concrete coating down to a depth of up to 25 cm.

4. The effect of the destruction of the concrete cover on the stability of the earth dam, the activation of filtration processes accompanied by increased suffosion of the underlying layer of the base of the reinforcement, were noted.

5. The filtration strength of the earth dam has been established, which is confirmed by theoretical calculations of the head gradient, ranging from 0,07 to 0,076, and the actual one from 0,04 to 0,15, which is significantly less than the critical one (1,5–4,0).

References

1. Hrebin, V.V., Khilchevsky, V.K., Stashuk, V.A., Chunaryov, O.V., & Yaroshevich, O.E. (2014). Vodnyi fond Ukrainy. Shtuchni vodoimy. Vodoskhovyshcha i stavky [Water Fund of Ukraine. Artificial reservoirs. Reservoirs and ponds] Kyiv: Interpres, 163 [in Ukrainian].
2. Khilchevsky, V.K., & Hrebin, V.V. (2021). Velyki i mali vodoskhovyshcha Ukrainy: rehionalni ta baseinovi osoblyvosti poshyrennia [Large and small reservoirs of Ukraine: regional and basin-specific distribution features]. *Hidrolohiia, hidrokhimiia i hidroekolohiia*, 2 (60), 6–17 [in Ukrainian].
3. Voroshilo, O. M., & Kleevska, V. L. (2013). Metodyka rozrakhunku naslidkiv hidrodynamichnykh avarii na prykladi Krasnopavlivskoho vodoskhovyshcha [Methodology for calculating the consequences of hydrodynamic accidents using the example of the Krasnopavlivsk reservoir]. *Teoriia i praktyka likvidatsii nadzvychainykh sytuatsii*. Lviv, 16–18 [in Ukrainian].
4. Bondar, O. I., Mykhailenko, L. E., Vashchenko, V. M., & Lapshyn, Yu. S. (2014). Suchasni problemy hidrotekhnichnykh sporud v Ukraini [Modern problems of hydraulic structures in Ukraine]. *Visnyk Natsionalnoi akademii nauk Ukrainy*, 2, 40–47. Retrieved from: http://nbuv.gov.ua/UJRN/vnanu_2014_2_8 [in Ukrainian].
5. Fareniuk, G.G., Vainberg, O.I., Khlapuk, M.M., & Shuminsky, V.D. (2019). Nadiinist ta bezpeka hidrotekhnichnykh sporud v umovakh tryvaloi ekspluatatsii [Reliability and safety of hydraulic structures under conditions of long-term operation]. *Nauka ta budivnytstvo*, 20 (2), 4–18. https://doi.org/10.33644/scienceandconstruction.v20i2.91 [in Ukrainian].
6. Panasyuk, I.V., & Tomiltseva, A.I. (2018). Shliakhy pidvyshchennia bezpeky hidrotekhnichnykh sporud Ukrainy [Ways to improve the safety of hydraulic structures in Ukraine]. *Aktualni pytannia enerhozberezhennia yak vymoha bezpeky zhyttiediialnosti*. Materialy Mizhnarodnoi naukovo-praktychnoi konferentsii. Kyiv, Osnova, 288–294. Retrieved from: https://ela.kpi.ua/handle/123456789/40401 [in Ukrainian].
7. Sankov, P, Dzyuban, O., Pylypenko, O., & Sydorka, V. (2022). Hidrotekhnichni sporudy: nadiinist i bezpeka isnuvannia ta ekspluatatsii [Hydraulic structures: reliability and safety of existence and operation]. Collection of scientific papers "SCIENTIA". *Tekhnolohii ta stratehii vprovadzhennia naukovykh dosiahnen*: I Mizhnarodna naukovo-teoretychna konferentsiia. Stockholm, 108–111. Retrieved from: https://previous.scientia.report/index.php/archive/article/view/79 [in Ukrainian].
8. Lotzman, P. I. (2017). Heodezychni zasoby kontroliu zminennia konstruktsii materialiv nyzhnoho biefu hidrotekhnichnykh sporud na prykladi Krasnopavlivskoho hidrovuzla [Geodetic means of control of changes in the construction of materials of the lower reaches of hydraulic structures on the example of the Krasnopavlivsk hydroelectric complex]. *Budivelni materialy ta vyroby*, 5–6, 77–79 [in Ukrainian].
9. Lotzman, P. I. (1998). Osnovnue napravlenyia vlyianyia hyd- rotekhnycheskykh system na PTK (na prymere Krasno-pavlovskoho vodokhranylyshcha) [The main directions of influence of hydrotechnical systems on PTK (on the example of the Krasnopavlivsk Reservoir)]. *Vestnyk KhHU*, 402, 89–92 [in Ukrainian].
10. Kleevska, V.L., Kruchyna, V.V., & Voroshilo, O. M. (2014). Informatsiina pidtrymka prohnozuvannia naslidkiv hidrodynamichnykh avarii [Information support for predicting the consequences of hydrodynamic accidents]. *Vidkryti informatsiini i kompiuterni intehrovani tekhnolohii*, 64, 206–211 [in Ukrainian].
11. Metodyka provedennia naturnykh obstezhen zemlianykh hrebel i zakhysnykh damb vodohospodarskoho pryznachennia [Methodology for conducting field surveys of earth dams and protective dams for water management purposes]. Posibnyk do VBN 13.2.4-33-2.3-2000. Rehuliuvannia rusel richok. Normy proektuvannia. (2000). Derzhvodhosp Ukrainy, 36 [in Ukrainian].
12. Klymenko, V. G. (2014). Krasnopavlivske vodoskhovyshche. Entsyklopediia Suchasnoi Ukrainy [Krasnopavlivsk reservoir. Encyclopedia of Modern Ukraine] NAN Ukrainy, Instytut entsyklopedychnykh doslidzhen NAN Ukrainy, Kyiv [in Ukrainian].
13. Betony vazhki. Tekhnichni umovy [Heavy concretes. Technical conditions]. (2022). DSTU 9208:2022. Derzhavnyi Natsionalnyi standart Ukrainy Kyiv: DP "UkrNDNTs" Ukrainy. Retrieved from: https://khsm.com.ua/images/articles/dstu_beton.pdf [in Ukrainian].

14. Betonni ta zalizobetonni konstruktsii. Osnovni polozhennia [Concrete and reinforced concrete structures. Basic provisions]. (2009). DBN V.2.6-98:2009. Derzhavni Budivelni Normy Ukrainy, DP "Derzhavnyi naukovo-doslidnyi instytut budivelnykh konstruktsii" (NDIBK). Rozrobnyk Derzhavne Pidpryiemstvo "Derzhavnyi Naukovo-Doslidnyi Instytut Budivelnykh Konstruktsii", 71. Retrieved from: https://e-construction.gov.ua/laws_detail/3200410998024438840?doc_type=2 [in Ukrainian].

15. Budivelni materialy. Sumishi betonni ta beton. Zahalni tekhnichni umovy [Building materials. Concrete mixtures and concrete. General technical conditions]. (2010). DSTU B V.2.7-176:2008 (EN 206-1:2000, NEQ), Derzhavnyi Natsionalnyi standart Ukrainy Kyiv: DP "UkrNDNTs" Ukrainy, 109. Retrieved from: https://www.ksv.biz.ua/GOST/DSTY_ALL/DSTU5/dstu_b_v.2.7-176-2008.pdf [in Ukrainian].

16. Dmitriev, A.F., Khlapuk, M.M., & Shuminsky, V.D. (1999). Hidrotekhnichni sporudy. [Hydraulic structures]. Pidruchnyk dlia vuziv, Rivne: RDTU, 328 [in Ukrainian].

17. Zakhyst vid nebezpechnykh heolohichnykh protsesiv, shkidlyvykh ekspluatatsiinykh vplyviv, vid pozhezhi. Zakhyst vid nebezpechnykh heolohichnykh protsesiv. Osnovni polozhennia proektuvannia [Protection against hazardous geological processes, harmful operational influences, and fire. Protection against hazardous geological processes. Basic design provisions]. (2009). DBN V.1.1-24:2009. Derzhavni Budivelni Normy Ukrainy, DP "Derzhavnyi naukovo-doslidnyi instytut budivelnykh konstruktsii" (NDIBK). Retrieved from: https://e-construction.gov.ua/laws_detail/3074285114079840009?doc_type=2 [in Ukrainian].

УДК 631.62:631.432:633.2

ОЦІНКА ТЕХНІЧНОГО СТАНУ ҐРУНТОВОЇ ГРЕБЛІ КРАСНОПАВЛІВСЬКОГО ВОДОСХОВИЩА

І.В. Войтович[1], канд. техн. наук, Я.В.Шевчук[2], О.М. Козицький[3], О.С. Ігнатова[4], Г.Я. Бойко[5],Ю.В. Лімачов[6]

[1] Інститут водних проблем і меліорації НААН, 03022, м. Київ, Україна;
https://orcid.org/0000-0002-1543-3955, e-mail: ivan.v.voytovich@gmail.com;
[2] Інститут водних проблем і меліорації НААН, 03022, м. Київ, Україна;
https://orcid.org/0000-0001-6718-3874; e-mail: yaroslav_shevchuk@ ukr.net;
[3] Інститут водних проблем і меліорації НААН, 03022, м. Київ, Україна;
https://orcid.org/0000-0002-4459-6331, e-mail: olegkoz@ukr.net;
[4] Інститут водних проблем і меліорації НААН, 03022, м. Київ, Україна;
https://orcid.org/0000-0002-2074-4555, e-mail: ignatovaoks@ukr.net;
[5] Інститут водних проблем і меліорації НААН, 03022, м. Київ, Україна;
https://orcid.org/0000-0002-2710-8543, e-mail: boykoG7@gmail.com;
[6] Інститут водних проблем і меліорації НААН, 03022, м. Київ, Україна;
https://orcid.org/0009-0008-5217-763X e-mail: leman4767@gmail.com

Анотація. *Греблі і дамби водосховищ відносяться до об'єктів підвищеної техногенної небезпеки, що зумовлено високою ймовірністю катастрофічного затоплення територій і руйнувань в результаті їх проривів. Ймовірність техногенних аварій на водосховищах зростає не лише із перевищенням проектних термінів експлуатації, але і внаслідок бойових дій та кліматичних змін, що призводять до зміни гідрологічного режиму поверхневих і підземних вод. За даними виконаних досліджень встановлено, що особливо піддаються руйнуванню монолітні залізобетонні кріплення верхових укосів гребель. Це, у першу чергу, пов'язано з руйнуванням температурно-деформаційних та конструктивних швів конструкцій кріплення, а також проявом хімічної та механічної суфозії. В результаті відбувається формуванням порожнин в основі кріплення тіла грунтової греблі, що призводить до просідання та руйнування кріплення, зменшення стійкості верхового укосу та проявлення фільтраційних процесів. З метою оцінки технічного стану конструктивних елементів грунтової греблі Краснопавлівського водосховища і встановлення потенційного резерву її експлуатації були проведені натурні обстеження, що дозволили оцінити стійкість як конструкцій кріплення, так і тіла грунтової греблі. Водосховище введене в експлуатацію у 1984 р, як складова частина гідровузла каналу Дніпро–Донбас. Воно забезпечує безперебійну роботу каналу, а у випадку аварійних ситуацій використовується як резервуар прісної води для водопостачання. Гребля водосховища грунтова. Верховий укіс у нижній частині закріплений кам'яним накидом, у верхній – монолітними залізобетонними плитами. Низовий укіс закріплений шаром ґрунту із посівом трав. Для розвантаження фільтраційних вод та відведення їх у відкритий дренажний колектор влаштовано трубчатий* *дренаж та розвантажувальні свердловини. Гребля в частині навантажень є характерною для більшості гребель водосховищ України. В ході виконання досліджень було використано комплекс діагностичних методів визначення , що включали неруйнівні обстеження бетонного покриття кріплення верхового укосу і оцінку його міцності із застосуванням молотка Шмідта, георадарні дослідження з визначення порожнин у товщі підстилаючого шару основи ґрунтової греблі під бетонним покриттям з використанням георадара VIY5 600, а також геодезичні методи вимірювання геометричних параметрів конструкцій споруд та наслідків руйнування конструктивних елементів. За матеріалами досліджень відмічено порушення геометричних параметрів греблі, наявність деформаційних процесів в частині просідання гребеня греблі в місцях проходження аномальних явищ. Відмічено вплив руйнування бетонного покриття на стійкість ґрунтової греблі, проявлення активізації фільтраційних процесів із супроводженням підвищеної суфозії підстилаючого шару основи кріплення.*

Ключові слова: *залізобетонне кріплення, земляна гребля, крива депресії, натурні дослідження, неруйнівні методи контролю, суфозія, технічний стан*

DOI: https://doi.org/10.31073/mivg202501-410
Available at (PDF): https://mivg.iwpim.com.ua/index.php/mivg/article/view/410

UDC 624.03;626;626.8

MONITORING OF DEFORMATION PROCESSES OF THE ELEMENTS OF ENGINEERING STRUCTURES OF HYDRAULIC FACILITIES

Y.A. Onanko, Ph.D.

Institute of Water Problems and Land Reclamation of NAAS of Ukraine, Kyiv, Ukraine;
https://orcid.org/0000-0002-7231-1188; e-mail: yaonanko1@gmail.com

Abstract. *Monitoring the technical condition of hydraulic facilities is crucial for ensuring their safe operation. This process usually involves monitoring environmental variables (e.g., concrete dam levels, temperature, piezometer readings), as well as geometric and physical variables (deformation, cracking, filtration, pore pressure, etc.), the long-term trends of which provide valuable information for facility managers. Research of the methods for analyzing geodetic monitoring data (manual and automatic) and sensor data is vital for assessing the technical condition and safety of facilities, especially when applying new measurement technologies. The age of hydraulic structures in Ukraine is 50–60 years and more, and their technical condition has deteriorated due to long-term operation. Their technical capabilities and reliability have decreased due to improper maintenance. In addition, insufficient consideration of environmental factors during operation has contributed to a decrease in the reliability of these structures.*

Most reservoirs and hydroelectric power plants were built in the mid-20th century and have been under constant operation. Due to significant operational life, negative changes often occur in their technical condition. Atmospheric, chemical, and other aggressive factors also contribute to the destruction of hydraulic facilities and their elements in water. This can lead to serious damage to both the facilities and the elements of hydraulic systems dependent on them. An additional negative impact factor on the condition of hydraulic facilities in Ukraine is missile and drone shelling and other damage as a result of military operations. Therefore, there is a need to develop a device that can be used when monitoring relative static and variable deformation, plasticity, and creep of samples from various elements of engineering structures, materials, elements, and assemblies in hydraulic engineering, construction, and industry.

Keywords: *deformation, hydraulic facilities, engineering structures, strain sensor, measuring device*

Relevance of the research. The factor influencing the environment is the technical condition of the hydraulic facility. Maintaining the structure in proper condition is an important aspect. It ensures the safety of the territories adjacent to the hydraulic facility. Maintaining the facility properly also eliminates the risk of environmental disaster and river pollution. Many existing hydraulic facilities are old, and their planned service life has exceeded [1–3]. It often happens that in cases of visible damage to the structure or its modifications, it is necessary to re-determine the static dimensions of the structure and calculate the necessary stability. To effectively detect damage, it is important to conduct a regular assessment of the technical condition of hydraulic facilities [4–6]. This is necessary for the proper functioning of the structure. Methods for assessing the technical condition developed by scientists using visual analysis and field measurements, as well as the latest technology, in particular laser scanning, are tools that significantly improve the work of specialists in the hydraulic field [7–9].

Deformations of soil foundations of hydraulic facilities, as a possible factor influencing the deformation processes of elements of engineering structures of hydraulic facilities, depend both on changes in volume (as a result of compaction, swelling, etc.), and on the deformation of individual soil phases (soil skeleton drift, of pore water compression, as well as inclusions of vapors and gases) [5–8]. An important influencing factor is the difference in the mechanical properties of the soil at different positions of the sample during the study, or the so-called mechanical anisotropy (for example, deformation anisotropy, strength anisotropy, swelling anisotropy), and sometimes the difference in filtration properties, or filtration anisotropy. The anisotropy of mechanical soil properties is explained by their ordered structure with a preferential parallel orientation of particles in a certain direction [2–4].

Analysis of recent research and publications. There are known devices for measuring deformations of structural elements [10-12] containing a strain gauge beam, which in turn contains a curved strain gauge element with support legs. To increase the reliability of the device, it has two permanent magnets, one of which is a groove. One reference line of the strain-element is rigidly fixed to one of the magnets and the other is freely mounted in the groove of another magnet and it has a base with lateral racks and a platform for mounting the racks, installed on the structure. Tensometric sensors are installed in the deformation areas of the base and racks [13].

The disadvantages of known devices are that they can only be used on laboratory samples, which are significantly different from the design in the defective structure, the low accuracy of measurement of relative deformation *ε*, and a limited class of the studied materials. The nearest analogue is a measurement device containing curvilinear strain-element with reference lines [14–17]. When deforming the sample the distance between the magnets changes, which leads to deformation of the strain-element, which is fixed by a measuring device [18–21]. The weakness of this device is the low accuracy of measuring relative deformation due to the small distance between the reference magnetic lines, as well as the limited class of studied materials.

Purpose of the research is to increase the sensitivity and reliability of measuring the relative static and variable deformation $\varepsilon = \frac{\Delta l}{l_0}$, plasticity, creep $\varepsilon = \frac{\partial}{\partial t}$ of the samples of the studied materials and the possibility of studying these processes in various elements of engineering structures directly during their operation after shelling with missiles, shells, and drones; expanding the class of engineering structures that are tested after deformations ε occurred as a result of military operations.

Materials and methods of the research. Field and laboratory experimental studies of monitoring deformations of structural elements of hydraulic facilities were carried out when using a developed device for measuring deformation ε of engineering structure elements.

Results of the research and their discussion. The goal is achieved by the fact that the proposed device has a strain element – an elastically curved strip with a strain sensor on it, which is connected to the electrical signal registration and recording system. The elastically curved strip is glued (welded) to an engineering structure element.

The design and operation of the device is explained by the drawing in Fig. 1 and Fig. 2. The design of the developed device is shown in Fig. 1. The device consists of an elastically curved strip, with a strain sensor on it, which is connected to the electrical signal registration and recording system. The elastically curved strip is glued (welded) to an engineering structure element.

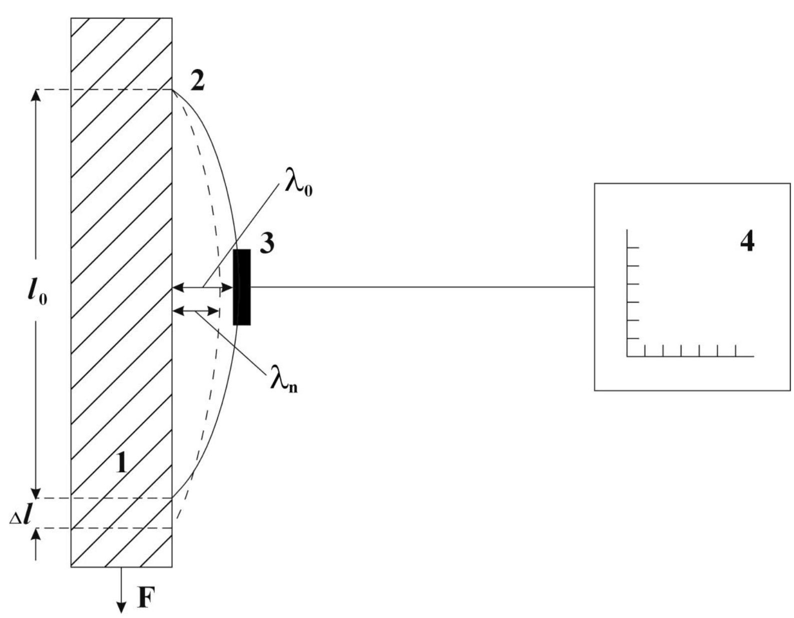


Fig. 1. Design of a device for measuring the deformation of engineering structure elements:
1 – engineering structure element, 2 – elastic bent strip, 3 – strain sensor, 4 – electrical signal registration and recording system

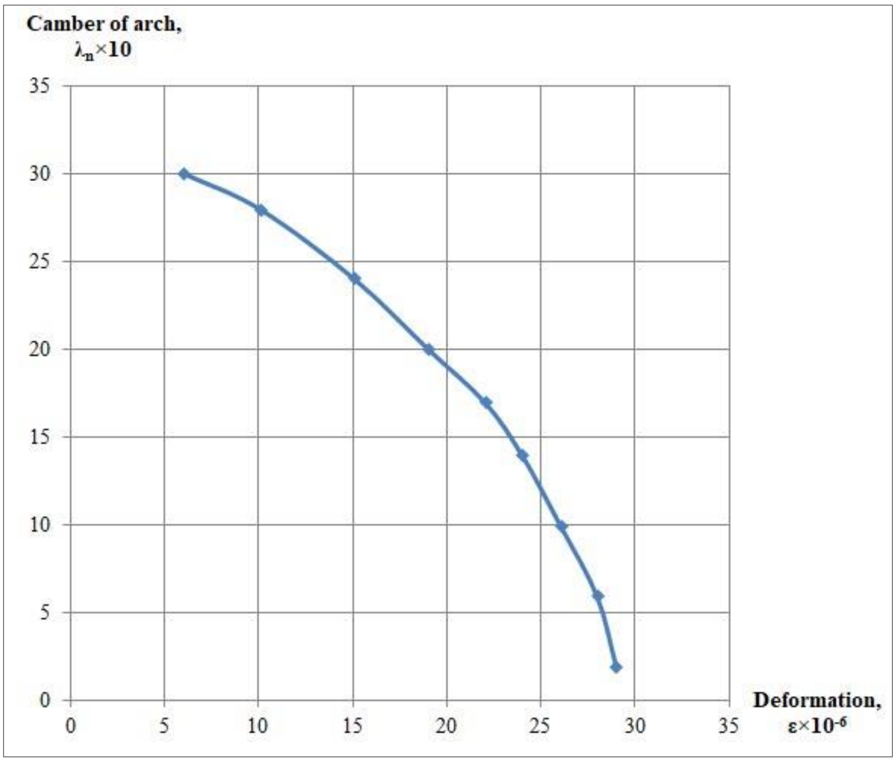


Fig. 2. Diagram of the dependence of an engineering structure element deformation $\varepsilon(\lambda_n)$ on the camber of arch λ_n of an elastic bent strip

Fig. 2 shows a diagram of the dependence of the deformation of an engineering structure element $\varepsilon(\lambda_n)$ on the camber of arch λ_n of an elastic bent strip. Deformation readings are obtained by a graphing measuring device, to which an electrical signal from a strain gauge is supplied.

The device works as follows. An elastic bent strip with a strain sensor on it is glued (welded) to the engineering structure element. A variable $\sigma(t)$ or constant σ_0 deformation stress is applied to the engineering structure element, which leads to a change in the length Δl of the engineering structure element, and, consequently, the camber of arch λ_n of the elastic bent strip. The magnitude of this bent λ_n is converted into an electrical signal by means of the strain sensor and recorded by a measuring device, a graph plotter.

The relationship between the relative static deformation $\varepsilon = \frac{\Delta l}{l_0}$ of the engineering structure element and the camber of arch λ_n of the elastic bent strip is described by the Chebyshev formula for a tensioning catenary [22–25]:

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{8}{3} \times \frac{\lambda_0^2 - \lambda_n^2}{l_0^2}, \quad (1)$$

where l_0 is the initial length of the engineering structure element, Δl is the change in the length of the engineering structure element, λ_0 is the initial length of the camber of arch of the elastic bent strip, λ_n is the camber of arch of the elastic bent strip with the changed length of the engineering structure element.

Thus, the proposed system of features provides the possibility of high-precision measurement of both plastic and elastic deformations ε based on the quadratic dependence $\Delta l \sim \lambda_n^2$ between the relative change in the length of the engineering structure element Δl and the and the camber of arch λ_n of the elastic bent strip glued (welded) to this element. The measurement of the values of the camber of arch $_n$ is made when using a strain sensor mounted on the specified strip. The proposed approach allows achieving a relative accuracy of deformation measurement at the level is $\frac{\Delta\varepsilon}{\varepsilon} \approx 10^{-7}$. The highest sensitivity of the device is achieved when the cambers of arch of the elastic strip are small $\frac{\lambda_0}{l_0} = 10^{-2} \div 10^{-3}$.

Conclusions. The task of creating a device for measuring the deformation *ε* of engineering structural elements was completed. The technical and economic advantages of the device over the most progressive similar technical ones are in simplifying the design and reducing the cost of devices implementing the proposed method. They make it possible to perform a periodic automatic, rather than continuous, control of the deformation ε of an engineering structural element, increase the accuracy of measurements of the deformation of an engineering structural element twice (elastic deformations ε with an accuracy of $\frac{\Delta\varepsilon}{\varepsilon} \approx 10^{-7}$ as well as expand the class of tested engineering structural elements, including non-magnetic ones.

References

1. Bestyński, Z., Sieinski, E., & Śliwiński, P. (2022). Geophysical investigation and the use of their results in the evaluation of the stability of slopes of artificial water reservoirs in the flysch Carpathians. *Archives of Civil Engineering*, 68(No 3), 71–85. https://doi.org/10.24425/ace.2022.141874

2. Cheng, L., Liu, Y., Pan, Y., Yang, Q., & Lv, Z. (2018). Effective stress law for rock masses and its application in impoundment analysis based on deformation reinforcement theory. *Journal of Central South University*, 25 (1), 218–229. DOI: https://doi.org/10.1007/s11771-018-3731-x

3. Kuzmych, L. (2007). Development of organizational and technical measures for keeping items of hydrotechnical structures in the good condition. Materials of scientific conference of young scientists. *The role of reclamation sustainable development of agriculture*, 19–21.

4. Hämmerling, M., Kocięcka, J., & Zaborowski, S. (2021). AHP as a Useful Tool in the Assessment of the Technical Condition of Hydrotechnical Constructions. *Sustainability*, 13 (3), 1304. DOI: https://doi.org/10.3390/su13031304

5. Issakhov, A., & Imanberdiyeva, M. (2020). Numerical Simulation of the Water Surface Movement with Macroscopic Particles of Dam Break Flow for Various Obstacles. *Water Resources Management*, 34 (9), 2625–2640. DOI: https://doi.org/10.1007/s11269-019-02382-w

6. Rokochinskiy, A., Kuzmych, L., & Volk, P. (2023). Handbook of Research on Improving the Natural and Ecological Conditions of the Polesie Zone. IGI Global. DOI: https://doi.org/10.4018/978-1-6684-8248-3

7. Koperska, W., Stachowiak, M., Jachnik, B., Stefaniak, P., Bursa, B., & Stefanek, P. (2021). Machine Learning Methods in the Inclinometers Readings Anomaly Detection Issue on the Example of Tailings Storage Facility. In E. Mercier-Laurent, M. Ö. Kayalica, & M. L. Owoc (Eds.), Artificial Intelligence for Knowledge Management (pp. 235–249). Springer International Publishing. DOI: https://doi.org/10.1007/978-3-030-80847-1_15

8. Prykhodko, N., Koptyuk, R., Kuzmych, L., & Kuzmych, A. (2023). Formation and Predictive Assessment of Drained Lands Water Regime of Ukraine Polesie Zone. In A. Rokochinskiy, L. Kuzmych, & P. Volk (Eds.), Handbook of Research on Improving the Natural and Ecological Conditions of the Polesie Zone, 51–74. IGI Global. DOI: https://doi.org/10.4018/978-1-6684-8248-3.ch004

9. Kowalska, M., Zaczek-Peplinska, J., & Piasta, Ł. (2024). Determining the trend of geometrical changes of a hydrotechnical object based on data in the form of LiDAR point clouds. *Archives of Civil Engineering*, 70 (1), 305–323. DOI: https://doi.org/10.24425/ace.2024.148913

10. Kuzmych, L., Furmanets, O., Usatyi, S., Kozytskyi, O., Mozol, N., Kuzmych, A., Polishchuk, V. & Voropai, H. (2022). Water supply of the ukrainian Polesie ecoregion drained areas in modern anthropogenic climate changes. *Archives of Hydro-Engineering and Environmental Mechanics*, 69 (1), 79–96. DOI: https://doi.org/10.2478/heem-2022-0006

11. Xujakulov, R., Rahmatov, M., Nabiev, E., & Zaripov, M. (2021). Determination of calculating stresses on the depth of loess grounds of hydraulic structures. *IOP Conference Series: Materials Science and Engineering*, 1030 (1), 012133. DOI: https://doi.org/10.1088/1757-899X/1030/1/012133

12. Zaczek-Peplinska, J., & Saloni, L. (2024). Modernising the control network for determining displacements in hydraulic structures using automatic measurement techniques. *Journal of Water and Land Development*, 59, 66–75. DOI: https://doi.org/10.24425/jwld.2023.147230

13. Onanko, Yu., Charnyi, D., Onanko, A., Dmytrenko, O., & Kuzmych, A. (2022). Oil and gas reservoir rock sandstone SiO2 porosity research by internal friction method. International Conference of Young Professionals "*GeoTerrace-2022*", 2022, 1–5. DOI: https://doi.org/10.3997/2214-4609.2022590062

14. Kutya, T. V., & Martynyuk, P. N. (2018). Mathematical Simulation of Humidification of Earth on a Slope and Calculation of Its Safety Factor. *Journal of Engineering Physics and Thermophysics*, 91 (5), 1189–1198. DOI: https://doi.org/10.1007/s10891-018-1848-2

15. Onanko, Y., Kuzmych, L., Onanko, A., Dmytrenko, O., Pinchuk-Rugal, T., Usatyi, S., Il'in, P., & Kuzmych, S. (2025). Influence of irradiation on indicatory surface of anelastic-elastic body of AgZn alloy. *Materials Research Express*, 12 (1), 016516. DOI: https://doi.org/10.1088/2053-1591/adabbc

16. Łydżba, D., Różański, A., Sobótka, M., & Stefanek, P. (2022). Optimization of technological measures increasing the safety of the Żelazny Most tailings pond dams with the combined use of monitoring results and advanced computational models. *Archives of Civil Engineering*, 68 (1), 503–518. DOI: https://doi.org/10.24425/ace.2022.140182

17. Onanko, A., Kuzmych, L., Onanko, Y., & Kuzmych, A. (2023). Indicatory surface of anelastic-elastic properties of Ti alloys. *Materials Research Express*, 10 (10), 106511. DOI: https://doi.org/10.1088/2053-1591/acfecc

18. Mazur, R., Stefanek, P., & Orlikowski, J. (2022). Corrosion monitoring as a factor increasing the safety of hydrotechnical infrastructure. *Archives of Civil Engineering*, 68(No 2), 197–209. DOI: https://doi.org/10.24425/ace.2022.140637

19. Onanko, Y., Kuzmych, L., Onanko, A., Il'in, P., & Kuzmych, A. (2024). Anelastic internal friction and mechanical spectroscopy of SiO2/Si wafers. *ECS Journal of Solid State Science and Technology*, 13 (4), 045001. DOI: https://doi.org/10.1149/2162-8777/ad36e0

20. Ospanov, N. S., & Krivchenko, A. A. (2021). Description of a 2-Year, High-Resolution Geodetic Monitoring of the Khoko Landslide, Enguri Reservoir, Georgia. In F. L. Bonali, F. Pasquaré Mariotto, & N. Tsereteli (Eds.), Building Knowledge for Geohazard Assessment and Management in the Caucasus and other Orogenic Regions (pp. 301–316). Springer Netherlands. DOI: https://doi.org/10.1007/978-94-024-2046-3_16

21. Onanko, A. P., Kuryliuk, V. V., Onanko, Y. A., Kuryliuk, A. M., Charnyi, D. V., Dmytrenko, O. P., Kulish, M. P., Pinchuk-Rugal, T. M., & Kuzmych, A. A. (2022). Mechanical spectroscopy and internal friction in SiO2/Si. *Journal of Nano- and Electronic Physics*, 14 (6), 06029. DOI: https://doi.org/10.21272/jnep.14 (6).06029

22. Ospanova, D., Dauletmuratova, N., & Aytmuratov, B. (2024). The results of the study on the technical condition of hydraulic structures in reservoirs. *E3S Web of Conferences*, 524, 02002. DOI: https://doi.org/10.1051/e3sconf/202452402002

23. Onanko, A. P., Kulish, M. P., Lyashenko, O. V., Prodayvoda, G. T., Vyzhva, S. A., & Onanko, Y. A. (2012). Inelastic-elastic properties of SiO2, SiO2 + TiO2 + ZrO2. 2012 IEEE International Conference on Oxide Materials for Electronic Engineering (OMEE), 2012, 81–82. DOI: https://doi.org/10.1109/OMEE.2012.6464790

24. Połomski, M., & Wiatkowski, M. (2024). Evaluation of the functionality of seepage prevention structures of dam bodies after a long period of operation – a case study of Otmuchów and Nysa reservoirs. *Archives of Civil Engineering*, 70(No 3), 153–171. DOI: https://doi.org/10.24425/ace.2024.150976

25. Stefaniak, K., & Wróżyńska, M. (2017). On possibilities of using global monitoring in effective prevention of tailings storage facilities failures. *Environmental Science and Pollution Research*, 25 (6), 5280–5297. DOI: https://doi.org/10.1007/s11356-017-0995-x

УДК 624.03;626;626.8

МОНІТОРИНГ ДЕФОРМАЦІЙНИХ ПРОЦЕСІВ ЕЛЕМЕНТІВ ІНЖЕНЕРНИХ КОНСТРУКЦІЙ ГІДРОТЕХНІЧНИХ СПОРУД

Ю.А. Онанко, Ph.D.

Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-7231-1188; e-mail: yaonanko1@gmail.com

Анотація. *Контроль за технічним станом гідротехнічних споруд має вирішальне значення для забезпечення їх безпечної експлуатації. Цей процес зазвичай включає відстеження змінних навколишнього середовища (наприклад, рівні бетонної дамби, температури, показання п'єзометрів), а також геометричних і фізичних змінних (деформація, розтріскування, фільтрація, поровий тиск тощо), довгострокові тенденції яких надають цінну інформацію для менеджерів об'єктів. Дослідження методів аналізу даних геодезичного моніторингу (ручного та автоматичного) та даних датчиків є життєво необхідними для оцінки технічного стану та безпеки об'єктів, особливо при застосуванні нових технологій вимірювання. Вік гідротехнічних споруд в Україні становить 50–60 років і більше, а їх технічний стан погіршився через тривалу експлуатацію. Їх технічні можливості та надійність знизилися через неналежне обслуговування. Крім того, недостатня*

увага до факторів зовнішнього середовища під час експлуатації сприяла зниженню надійності цих конструкцій.
Більшість водосховищ і гідроелектростанцій були побудовані в середині 20 століття і з тих пір постійно використовуються. Через вік в їх технічному стані часто відбувалися негативні зміни. Атмосферні, хімічні та агресивні фактори також сприяють руйнуванню гідротехнічних споруд та їх елементів у воді. Це може призвести до серйозних пошкоджень як самих споруд, так і залежних від них елементів гідротехнічних систем. Додатковим фактором негативного впливу на стан гідротехнічних споруд в Україні стали обстріли ракетами, снарядами, дронами та інші ушкодження одержані внаслідок воєнних дій. Тому виникала потреба в розробці пристрою, що може бути використаний при дослідженні відносної статичної та змінної деформації, пластичності, повзучості зразків з різних елементів інженерних конструкцій, матеріалів, елементів, вузлів у гідротехніці, будівництві, промисловості.
Ключові слова: *деформація, гідротехнічні споруди, інженерні конструкції, тензодатчик, пристрій для вимірювання*

ЗМІСТ

CONTENTS

НОТАТКИ
NOTES

Наукове видання

Меліорація

і водне господарство

№ 1 • 2025

Міжнародний журнал

Заснований у 1965 році

(Випуск 121)

Виконавчі редактори – К. Б. Шатковська, Н. В. Логунова, О. П. Войтович

Підписано до друку 30.06.2025 р.
Формат 60×84/8. Папір офсетний.
Цифровий друк. Гарнітура Times New Roman.
Ум. друк. арк. 13,72. Обл. вид. арк. 10,25.
Наклад 100. Замовлення № 0725-010.

Видавництво та друк: Олді+
65101, м. Одеса, вул. Інглезі, 6/1
тел.: +38 (095) 559-45-45, e-mail: office@oldiplus.ua
Свідоцтво ДК № 7642 від 29.07.2022 р.

Замовлення книг:
тел.: +38 (050) 915-34-54, +38 (068) 517-50-33
e-mail: book@oldiplus.ua